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Lunar Surface Operations

Volume IV:
Lunar Rover Trailer

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Lunar Rover Trailer

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ABSTRACT

The purpose of the project was to design a lunar rover trailer for exploration missions. The trailer was designed to carry cargo such as lunar geological samples, mining equipment and personnel. It is designed to operate in both day and night lunar environments. It is also designed to operate with a maximum load of 7000 kilograms. The trailer has a ground clearance of 1.0 meters and can travel over obstacles 0.75 meters high at an incline of 45 degrees. It can be transported to the moon fully assembled using any heavy lift vehicle with a storage compartment diameter of 5.0 meters. The trailer has been designed to meet or exceed the performance of any perceivable lunar vehicle.

1.0 Introduction

1.1 Statement of Need

It has been almost a quarter of a century since man's first visit to the moon. In that time there have been a variety of reasons proposed for returning to the moon. One of the most discussed of these reasons is for the purpose of exploration mining. The moon is a vast island of resources orbiting around the earth just waiting to be discovered and utilized.

It is with this in mind that the need for a lunar rover trailer becomes viable. It would serve as a piece of equipment which would travel behind a lunar vehicle, facilitating the transportation needs of the exploring lunar miners and their respective missions. Such a vehicle must be able to endure the rigors of the extreme lunar environment. It must also be able to traverse the lunar geography, filled with craters and soft soil.

The payload that a lunar trailer might be required to carry on a mining expedition include samples such as sand and rocks, mining equipment (picks and shovels) and mining personnel (over short distances). Also the design must take into account how the trailer will be transported from the earth to the moon. In addition, due to the lack of budget constraints for this design project, the materials best suited for this design were selected for the trailer. However, this would result in a greater overall cost in the manufacturing process.

1.2 Objectives

1. Traverse 0.5 meter obstacles.
2. Ascend 30° slope.
3. Have a load capacity of at least 300 N.
4. Must be able to withstand 400 N of towing force.

5. The vehicle should be able to be transported fully assembled in a cylinder 20 meter long with a 5 meter diameter. (These are the dimensional constraints of a NASA heavy lift vehicle.)
6. Must have a mass less than 30,000 kg. (Heavy lift vehicle capacity.)
7. Maintain operational orientation without being attached the vehicle (free-standing).

1.3 Task Organization

The task activities have been planned to compare different trailer system approaches for implementing lunar transportation vehicle trailers and to utilize the comparative analyses to provide different conceptual designs.

The strategy for the study is to provide analyses and designs which are applicable to current advanced program planning, but are not directed at mission targets so specific as to be invalid when program evolution changes mission definitions.

An effort has been completed to survey earlier lunar surface transportation systems documentation. The findings of this survey were used in order to analyze the respective designs and materials to be discussed.

The transportation trailer system has been separated into several different topics for purposes of performing comparative analyses of the relative merits in the alternative designs. At this embryonic stage of mission definition, the analyses generally identify advantages and disadvantages of certain features. Identification of the best design approaches must be deferred until later design iterations when more specific, integrated mission specifications are appropriate. Section III is the documentation of the trailer systems comparison analyses. The corresponding figures of the analyses are included in Section IV.

Finally Sections' V and VI are respectively the references of the gathered information and the Appendices in which are included the calculations and other related data.

2.0 Task Guidelines

2.1 Lunar Terrain Guidelines

This section defines the terrain parameters which affect the surface propulsion, navigation, and communications systems of vehicles and their trailers moving on the lunar surface. The trailers are assumed to be hitched to vehicles which operate in recent lunar sites of interest which can be characterized by data from previous landings and photos of other sites. Two of the four sites lie on flat mare surfaces surrounded by mountains (Lacus Veris and Taurus Littrow), one lies purely in flat mare (Nubium), and one is a rugged highlands region (South Pole). Data of the type and quality required to plan detailed distances is available for only Taurus Littrow, site of the Apollo 17 landing. These data consist of Apollo 15 and Apollo 17 Pan camera pictures with a resolution of less than 5 meters (16 ft) and the metric camera pictures with a resolution of about 20 meters (66 ft). The later was coupled to the laser altimeter and provides the best geodetic data base for the moon. Data on the Lacus Veris and Nubium landing sites is limited to Lunar Orbiter IV imagery with a resolution of 60-65 meters (197-213 ft). The imagery of the South Pole is limited to Lunar Orbiter IV images with most of the region in shadow. These images suggest that the South Pole is extremely rugged highlands terrain.

Because the lunar soil has a relatively constant bearing strength, mobility will not be constrained by the presence of unusually soft soil anywhere. The principal barriers that are expected are steep slopes and boulder fields at the rims of fresh craters as well as certain other materials which will be mentioned in the ensuing discussion. This section defines aspects relating the impact of terrain on lunar surface transportation trailer design. These lunar terrain topics are: 1) the mixture of slopes likely to be encountered, 2) the presence of barriers to movement, 3) soil bearing strength, and 4) surface topography.

2.1.1 Surface Slope Distribution

Published slope data is available for all of the candidate Apollo landing sites as

well as a large number of other areas of the moon. These sets of data are represented in Figures 1-4 and Table 1 attached. It should be noted that although there are extreme variations in the long wavelength portions of the slope spectrum, the shortest slope wavelengths of 25 meters (82 ft) are relatively constant for the mare or highland plains at 4-6°. Figure 3 shows the slope data in a graphical manner which emphasizes the obvious: slopes are less on the mare than in the uplands or highlands, with the highland plains unit, the Cayley plains, being intermediate between the two. For example at Apollo 17, the landing site was in the flat mare floored valley with average slopes of 57°. In contrast, the slopes of the flanking North and South Massif have slopes of 20-30°. Figures 2, 3, and 4 show areal basis. In this manner it is possible to plan traverses to avoid the steep slopes. For example, the only major terrain impediment at the Apollo 17 landing site was the Lee-Lincoln Scarp. A pass with modest slope, however was identified in the Apollo 15 pictures and that pass was used by the Apollo 17 Lunar Rover Vehicle (LRV). In future missions, similar planning can essentially eliminate the limits on mobility due to steep slopes, assuming that adequate photography is available.

2.1.2 Barriers to Movement and Surface Roughness

The empirical observation of the Apollo program was that local surface roughness which might affect the mobility of a vehicle came exclusively from recent impacts, associated with bright rayed craters. These events throw out large and small angular blocks for distances of several crater diameters. With time, these rocks are comminuted to fine lunar soil by micro-meteorite impacts which also darken the soil. The process is extremely slow by terrestrial standards, a few million years are required to simply round off the corners of the boulders several meters across such as those seen at Apollo 17 Station 6. The best documentation of an ejecta block field on the moon was that of South Ray Crater, a 2.5 million year old crater 0.5 km (1640 ft) across at the Apollo 16 landing site. Blocks from this event littered the south half of the landing site. South Ray was

approached within seven crater diameters or 3.5 km (2.2 miles) where the blocks covered a few percent of the surface. Conditions probably become impassable only within one crater radius or 250 m (820 ft) from the rim. Only a very small number of craters are young bright rayed craters less than 100 million years old.

2.1.3 Soil Mechanics

The lunar surface consists of a fine grained soil with a significant amount of material finer than 0.05 mm (0.002 in). The fragments are mostly silicate mineral fragments and glass with a fraction of a percent metallic iron. The soil at all points studied in detail by Apollo, Surveyor, Luna, and Lunikhood spacecraft consisted of a porous zone a few centimeters thick at the surface which graded into progressively more and more compacted material with depth. Soil thickness is generally related to the age of the rocks nearest the surface. The older the rocks, the thicker the soil. However, there is significant local variation in the thickness of the soil due to the presence of craters over a hundred meters across which penetrate into bedrock. In general, the soil layers are 2 to 5 meters (6.6 to 16.4 ft) thick on the mare. The soil in highland areas lacks a well defined base because the bedrock consists of coarse rubble and breccias disrupted by craters tens of kilometers across.

The physical properties of the soil are dominated by its degrees of combination by micro-meteorites and its packing. Grain size effects and the abundance of small glass bound fragments called agglutinates play a more critical part in soil physical properties than chemical or mineralogical composition of the bedrock. Grain size and composition effects are in turn dominated with the effect of packing. The first observation from Apollo core samples is that the packing density is very loose at the surface and increases sharply in the top few centimeters. The second observation from Apollo core samples is that soil agglutinate content decreases and grain size increases with depth (Figure 5). Craters which are surrounded by light colored material have sharp well defined rims and

an abundance of blocks of bedrock. Near these fresh craters, the grain size of the soil is generally coarser than dark colored soils away from such craters. The process of destroying the blocks, comminuting the soil, and building up the agglutinate content is very slow. The young fresh crater, Cone, sampled by Apollo 14 is about 25 million years old. Tycho, the large bright crater readily visible from earth using a pair of binoculars, is thought to be about 75-110 million years old.

The definition of requirements placed on vehicles by the soil bearing strength and related factors should be treated generally for the entire moon since the dominating factors vary over a scale of several hundred. Table 2 (attached) summarizes the soil physical properties for the Apollo 14 through 17 landing sites. As a reference, note that an astronaut boot or the Apollo lunar module both place a stress on the surface of about a pound per square inch (0.69 N/cm^2 or 6.9 kN/m^2). Such stresses result in penetration of the lunar surface of less than a centimeter to a few centimeters. The angle of internal friction of lunar soil is also summarized in Table 2. The angle of 36° to 42° is equivalent to the angle of repose for loose soil such as on the side of a mountain. The tangent of the angle is equal to the coefficient of internal friction, 0.73 to 0.90. The cohesion of the soil is 0.01 to 0.1 N/cm^2 and like other properties increases with packing density and depth.

Data on the Apollo LRV indicates the amount of electrical power required to overcome the resistance of rolling over the moon. The Apollo LRV has a loaded mass of 708 kg(1,561 lbs). Figure 6 gives the power drawn from the LRV batteries. Using approximate numbers, the rover required 60 wh/km (1,800 wh over 28 km) on Apollo 15; 80 wh/km (2,880 wh over 35 km) for Apollo 17; and 100 wh/km (2,700 wh over 27 km) for Apollo 16. The higher power draw of the Apollo 16 mission reflects the highland terrain, which was more rugged than that traversed at Apollo 15 or 17.

2.1.4 Surface Topography

It is assumed that all traverses whether for science, resource exploration, or base logistical support will be preplaned to some extent. Initially, traverses will have to be

planned and practiced with the thoroughness of Apollo J mission traverses. Once the operating characteristics of the vehicle are well known, planning more typical of terrestrial explorations should be sufficient, where the crew need only be given a detailed traverse plan, a navigation system update of key reference points, and maps showing the planned traverse. Such a level of planning is sufficient to eliminate the possibility of having the traverse plan affected by insurmountable scarps or dense boulder fields which require a slow meandering path around the obstructions.

Navigation within a few kilometers of the base is easily accomplished using landmark tracking, probably supplemented by data derived from line of sight communication between the base and the transportation vehicle. Planning traverses of significant distances is greatly enhanced by knowing what the terrain will be like in advance. Such data is typically recorded on topographic maps whether in hard copy or digital format. The data which is needed includes both contour lines, displaying the elevation and slope data, and data on the presence of small scale features such as ejecta from fresh young craters. Navigating traverse vehicles will certainly be done relative to landmarks on the ground, whether the vehicle is controlled by a human driver or some type of automated system. Furthermore, the detailed planning of traverses requires maps of sufficient quality to identify slopes which exceed the capabilities of the vehicle or areas with blocking ejecta from recent craters which would require a serpentine traverse path around the blocks. In essence, operating traverse vehicles will require the same quality data used for similar activities on earth such as geological surveys in remote wilderness areas. Those data are equal to those required to produce topographic maps approximately the quality of the standard 1:24000 scale maps available for most of the United States from the U.S. Geological Survey. Such maps have all points located laterally within 61 m (200 ft) and vertically within about 3 m (10 ft) in areas of low relief such as mare. The maps will certainly have to be prepared by photogrammetric techniques with the map locations tied together with a benchmark system. Such a system

would have a small number of positions known with great precision and accuracy and a far larger number of positions known to a lower level of precision. The requirements are different from those required for landing sites because the absolute geodetic reference frame is not particularly significant for traverse vehicles. It is only the relative elevation differences of points (bench marks) that must be established within a few feet. These requirements imply the existence of data of a type that exceeds that defined for the Lunar Geoscience Observer. The amount of territory that must be accurately imaged is only that accessible or visible to the traverse vehicles.

2.2 Environmental Effects

2.2.1 Temperature

The lunar vehicles will be exposed to widely varying temperatures from -233 to 127°C (40 - 400°K) during their respective missions and therefore must be designed to isolate the pressurized cabin of the LRV from its exterior environment. The vehicle and its propulsion system can be viewed as a heat source which will require some sort of heat rejection capability. Much of this heat can be used to keep the vehicle warm during cold soaking periods (night time). However, hot soaking periods (day time) the thermal control system must be designed to reject heat excess. These factors however, would not need to be considered for the trailer portion of the vehicle. These temperatures will however have an effect on the materials which is why certain materials were selected.

2.2.2 Radiation

Earth orbital operations at low altitudes and low inclinations are protected from solar proton events from the earth's magnetic field. The chances of encountering a solar proton event during the short duration Apollo missions was small and no major event was encountered. For extended operations on the lunar surface, neither of these protective

conditions are present. There is no magnetic field around the moon and near-continuous occupancy of the lunar surface is planned. Major solar flares can be expected in the period 1999 to 2004. Thus more stringent protection from such events must be incorporated into lunar surface transportation mission planning.

The stay-times on the lunar surface are planned to gradually increase until they are 180 days in duration. This prolonged period under reduced gravity conditions will cause physiological changes which currently are not completely or well understood. To date reduction in bone calcium and muscle density and changes in the red blood cells have been observed. Table 3 shows the threshold for acute radiation effects. These effects are caused by high radiation doses delivered in a brief period of time (1-4 days or less). The symptoms shown in this table are derived from data obtained under one-g conditions and it is anticipated that they will occur at lower levels for crew members who have been in reduced gravity for an extended period. In Table 4 it can be seen that these acute radiation effects may be delayed from periods of from three to four weeks. Recovery from radiation damage is not well understood. The National Council On Radiation Protection and Measurements reported in NCRP Report No. 29, January 1969, that 10% of all radiation produced permanent damage and that recovery from the balance of damage occurred at a rate of 2.5% per day. This data was considered applicable only to the acute effects of radiation and admitted that "... the whole question of time-intensity variation is so complex that each situation will undoubtedly require its own interpretation".

2.3 Mission Guidelines

In order to develop conceptual designs of lunar surface transportation vehicles and their trailers, guidelines are required which baseline the functional vehicle and trailer performance required to accomplish the anticipated missions. This section defines a generic baseline for the mission objectives to be achieved during lunar traverse missions.

Activity and equipment requirements necessary to implement the objectives are described in order to derive the payload and trailer definition parameters. Several baseline traverse missions are defined that accomplish the majority of the mission objectives. Finally, transportation trailer functional performance requirements are specified as a baseline for guiding the conceptual designs of the vehicles.

2.3.1 Non-Base Surface Mission Objectives

Surface traverses away from the base will attempt to accomplish many objectives. Primary among these are to assist the LRV in its attempts to study the structure, tectonism, cratering history, petrology, mineralogy, stratigraphy, age, development history, resources, and morphology of the lunar surface and crust. Success of the mission objectives will depend on the ability to perform experiments at geographically diverse locations. Some activities will occur over contiguous surface features, while others will concentrate on a single feature. Some experiments will require activities to be performed at specific locations remote from the lunar base, while others can be performed near the base. Features that will be of interest include craters, rim deposits, ejecta blankets, rills, fault scarps, volcanic complexes, mare regions, highland regions, and mountains.

2.3.2 Payload Equipment Requirements

It is assumed that, for local traverses within kilometers of the lunar base, samples and data will be collected during the traverse and returned to the base for analysis. For longer traverses (hundreds of kilometers and several weeks or more), it may be more effective to perform the analysis at the collection site and leave most of the samples behind. A list of potential tools and equipment required to perform three categories of surface activities has been compiled. This data is summarized in Table 5 and further discussed in the following paragraphs.

Surface sample collection will require such tools as rock hammers, tongs, rakes, scoops, shallow drills, core tubes, sample collection bags, and sample storage boxes. These tools occupy approximately 0.3 cubic meters (10.6 ft^3), have a mass of approximately 80 kilograms (176 lbs), and require about 0.5 kilowatts of power when used.

Selenophysical experiments will assist in mapping the seismic, magnetic, and electrical properties of the subsurface and its density variations. Equipment for these experiments could include profiling active seismic arrays, thumpers, explosive packages, a magnetometer, a gravimeter, and an electrical properties experiment package. This equipment occupies approximately 0.4 cubic meters (14.2 ft^3), has a mass of approximately 650 kilograms (1,433 lbs), and requires about 0.1 kilowatts of power when used.

Equipment for selenogy exploration could include cameras, film, a stadiametric range finder, a sun compass/azimuth indicator, an inclinometer, and a trenching tool. This equipment occupies approximately 0.3 cubic meters (10.6 ft^3), has a mass of approximately 150 kilograms (330 lbs), and requires about 0.5 kilowatts of power when used.

2.3.3 Mission Definitions

Three baseline mission types illustrate most of the scenarios that a lunar surface transportation vehicle will encounter. These are local traverse, a long-range surface applications mission, and the ability to traverse to a remote location to accomplish a localized mission. The trailer must be able to accomplish these same functions as it will have to be able to maintain at least the standards and requirements of the vehicle itself.

The local transportation mission would use an unpressurized vehicle for deploying experiments, collecting samples, surveying, and transportation near the lunar base. As many as four personnel would be transported. Teleoperation of the vehicle would allow

completion of simple errands without requiring crew EVA. Its operating range would be constrained by the distance it could travel out from the base and back in one work day. Total EVA time per day per crewman is assumed to be about eight hours. Assuming a minimum desired productive mission work time of one hour, maximum driving time would be seven hours per trip. The vehicle for this mission is designated as the Local Transportation Vehicle (LOTRAN).

Trips to conduct lunar surface science and utilization applications require travel at long ranges from the lunar base. This type of mission would last from several days to many weeks and thus, would require a pressurized vehicle. Activities performed during this mission would include surface and deep drill sample collection, prospecting, surveying, and the deployment of geophysical experiments over one or more geographical features. The mission would be constrained by the size of the feature or features to be explored, and could range for hundreds of kilometers. Such a long duration would require the vehicle to combine the features of a habitation module and a laboratory in the form of a mobile transportation vehicle.

Many of the surface activities, such as sample collection and drilling, could be performed in a teleoperated mode from inside the vehicle. Other activities, such as equipment deployment, surveying, and collection of hard-to-access samples, would require EVA.

Four crewman are planned for the long range surface applications mission. Using rotating crew shifts, the vehicle would be driven for up to twelve hours per Earth day. The vehicle for this mission is designated as the Mobile Surface Applications Traverse Vehicle (MOSAP).

During the remote location mission, a team of astronauts would fly from the base to a remote location and perform surface applications activities within five to ten kilometers (3.1 to 6.2 miles) of the landing site. Due to the fact that this would require a vehicle capable of ballistic flight, soft landing, and return, this has no bearing on any

analysis done on the vehicle thus none on the trailer either. Therefore, this topic will not be discussed in detail although some of the analyzed data are included Table 6 under the heading for the Ballistic Transportation Vehicle (BALTRAN).

2.3.4 Trailer Functional System Requirements

Based on the development of the baseline mission guidelines, the vehicle functional performance requirements have been identified and documented in Table 6. For the vehicle to be used in each of the three types of missions, functional performance requirements are designated as "Required" or "Desired". These requirements are somewhat simplified in the case of the trailer and these specifications will be discussed in a latter portion of the analysis.

Figure 1: Comparison Between Algebraic Standard Deviation and Mean Absolute Slopes for Lunar Slope-Frequency Distributions.

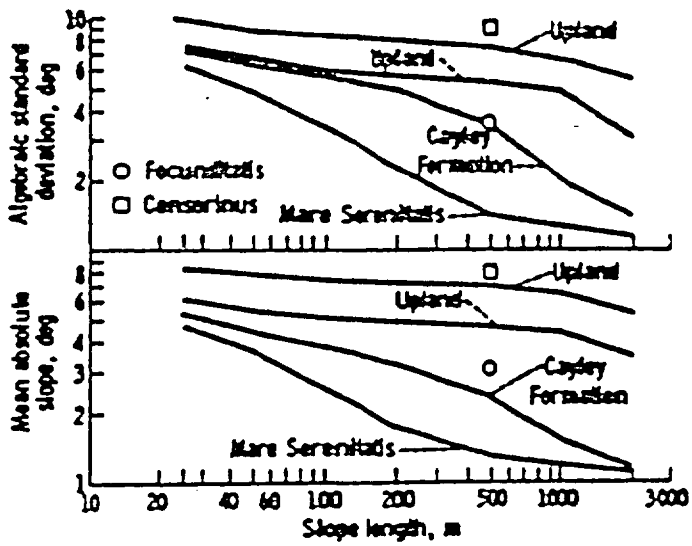
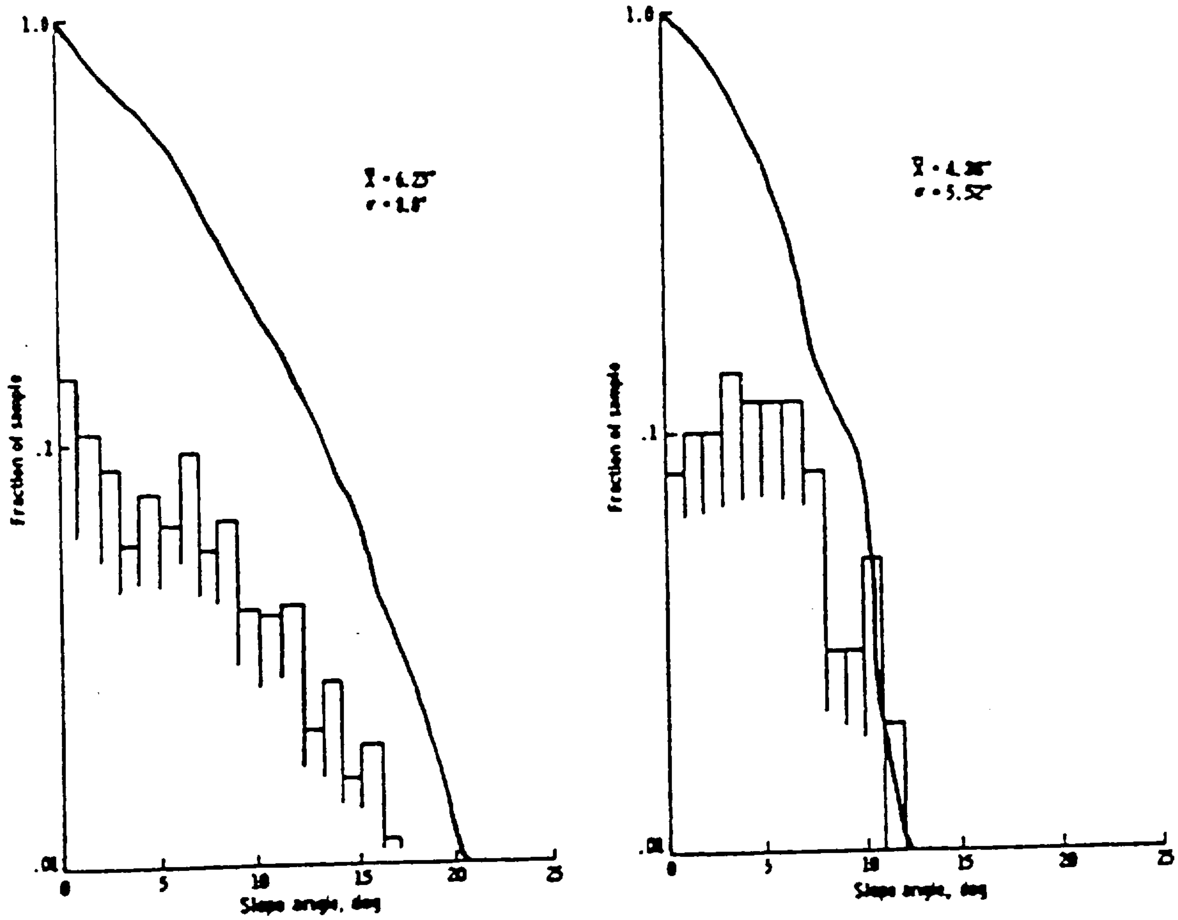


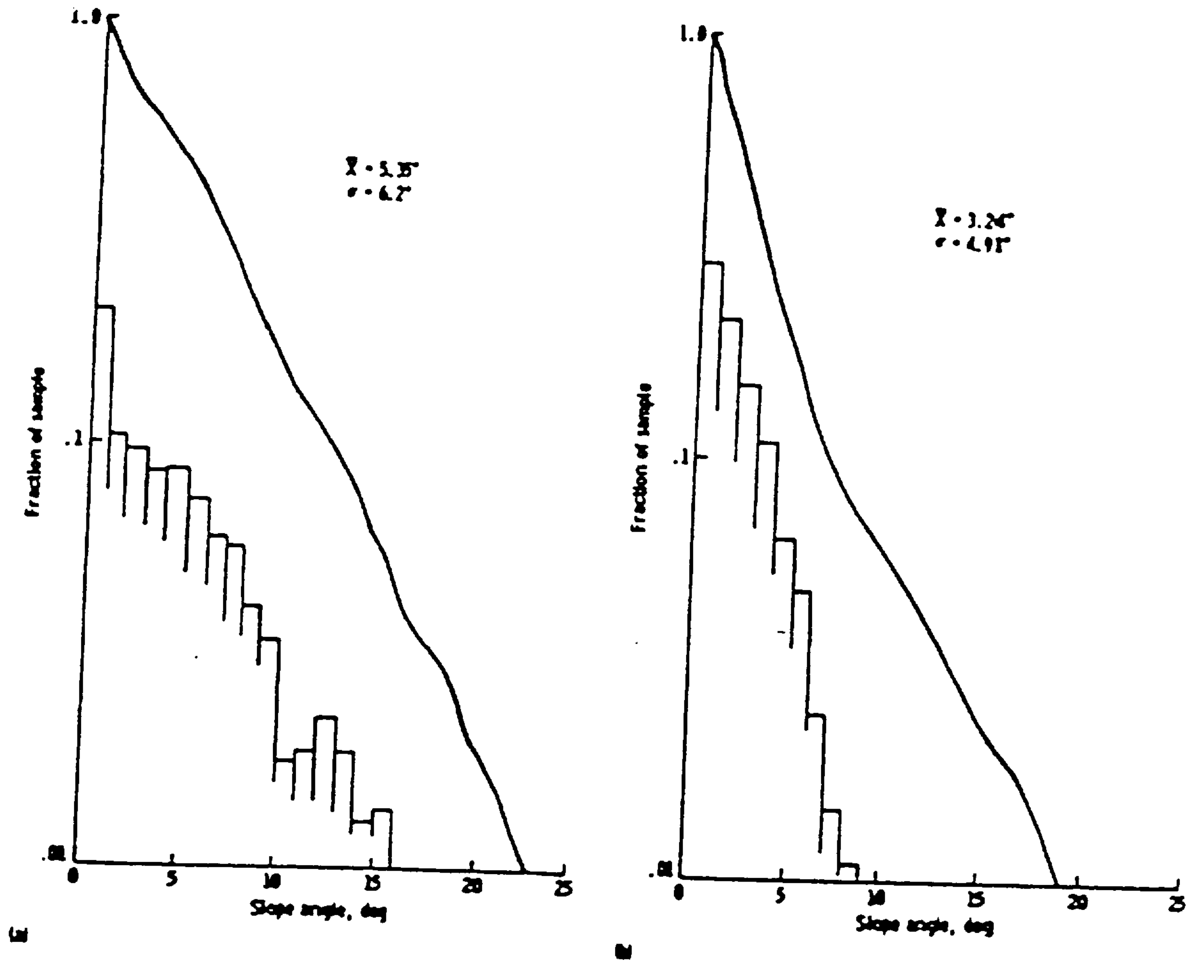
Figure 2: Upland Distribution of Slope Values, North of Vitruvius (from Ref. 70)



(a) (b)

Frequency distribution of absolute slope values for upland surface north of Vitruvius. Bars represent fraction of sample for 1° increments of slope angles. Solid lines indicate cumulative fraction of sample with absolute slopes larger than angle indicated. The quantity $\bar{X}$ is the mean absolute slope and σ is algebraic standard deviation of distribution. (a) Slope length ΔL 25.2 m. (b) Slope length ΔL 201 m.

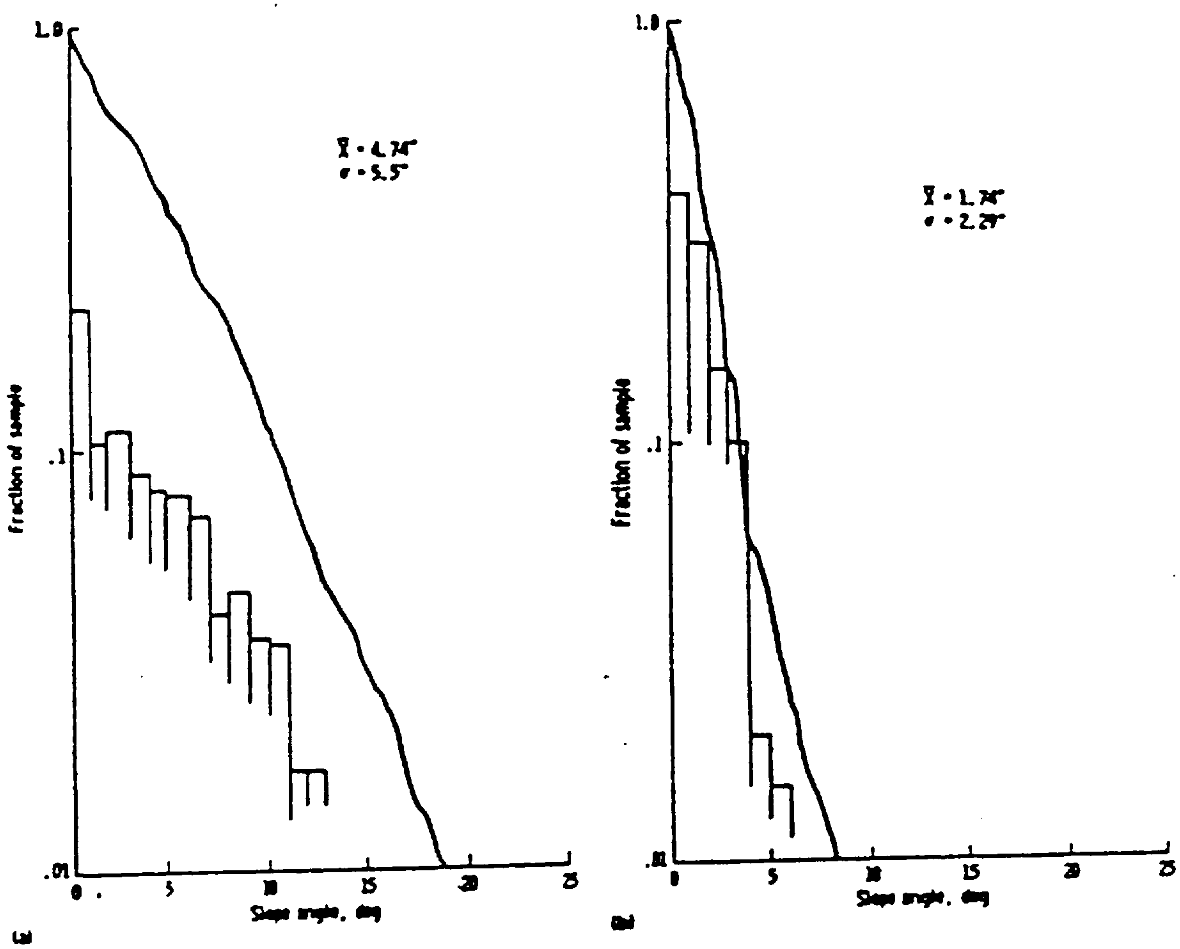
Figure 3: **Upland Distribution of Slope Values, Cayley Plain at Apollo 16 Landing Site (from Ref. 70)**



Frequency distributions of absolute slope values for Cayley Plain at the Apollo 16 landing site. Bars represent fraction of sample for 1° increments of slope angle. Solid lines indicate cumulative fraction of sample with absolute slopes larger than angle indicated. The quantity $\bar{X}$ is mean absolute slope and σ is algebraic standard deviation. (a) Slope length ΔL 25.1 m. (b) Slope length ΔL 201 m.

Figure 4:

Mare Distribution of Slope Values, Mare Serenatatus (from Ref. 70)



Frequency distribution of absolute slope values for surface in Mare Serenitatis. Bars represent fraction of sample contained in 1° increments of slope angle. Solid lines indicate cumulative fraction of sample with absolute slopes larger than angle indicated. The quantity $\bar{X}$ is mean absolute slope and σ is algebraic standard deviation of distribution. (a) Slope length ΔL 25 m. (b) Slope length ΔL 200 m.

Figure 5:

Penetration Resistance of Lunar Surface at Various Locations (from Ref. 46)

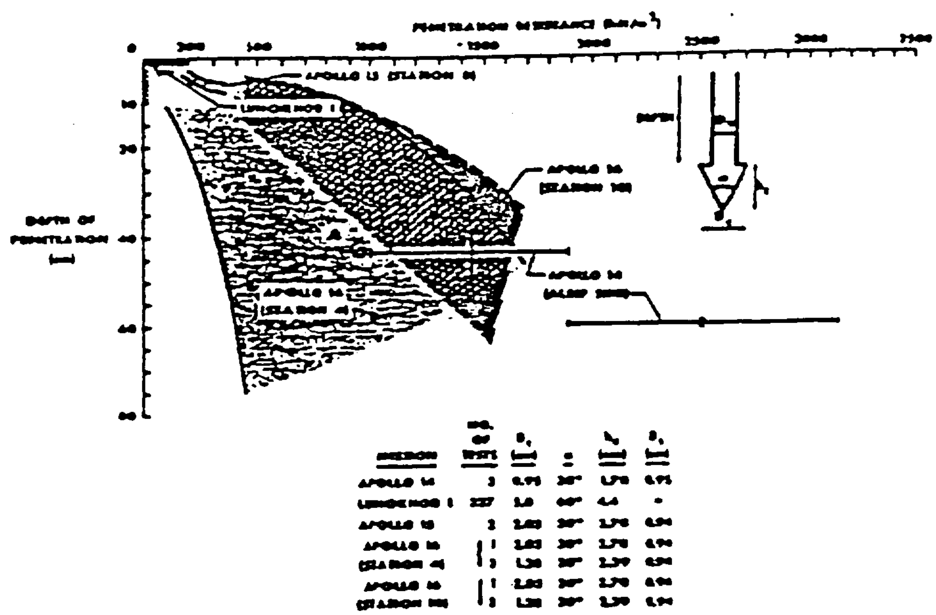


Table 1:

Slope Data for Lunar Surface as a Function of Length of Segment Measured (from Ref. 78)

Terrain type	*Algebraic standard deviation, deg*						*Mean absolute slope, deg*					
	ΔL 25 m	*ΔL 50 m*	*ΔL 100 m*	*ΔL 200 m*	*ΔL 500 m*	*ΔL 1000 m*	*ΔL 25 m*	*ΔL 50 m*	*ΔL 100 m*	*ΔL 200 m*	*ΔL 500 m*	*ΔL 1000 m*
Mare Serenitatis	5.8	4.8	3.4	2.3	1.4	1.2	4.7	3.7	2.5	1.7	1.3	1.2
Mare Serenitatis	6.1	4.9	3.6	2.5	1.3	.8	4.8	3.8	2.8	1.8	1.0	.7
Cayley Plain	6.2	6.3	5.6	4.9	3.4	1.5	5.4	4.5	3.8	3.2	2.3	2.0
Uplands, near Proclus	6.4	6.0	5.0	4.3	3.2	2.2	5.4	4.6	3.9	3.3	2.6	2.1
Uplands, north of Vitruvius	7.8	6.6	5.9	5.5	5.2	4.7	6.2	5.5	5.1	4.9	4.7	4.3
Uplands, near Glaisher	9.9	8.8	8.2	7.8	7.3	6.7	8.4	7.9	7.5	7.3	6.9	6.4
Mare Fecunditatis	–	–	–	–	3.6	2.6	–	–	–	–	3.1	2.0
Uplands, near Censorinus	–	–	–	–	10.5	9.2	–	–	–	–	7.8	6.3
Littrow, landing site	4.5	–	–	–	–	–	3.8	–	–	–	–	–
Littrow, west of landing site	4.6	–	–	–	–	–	3.9	–	–	–	–	–
Hadley, landing site	6.8	–	–	–	–	–	5.7	–	–	–	–	–

Table 2:

Average Material Properties of Surficial Lunar Soil at Apollo 14-17 and Luna Landing Sites (from Ref. 46)

Soil consistency	G,[a] N/cm^3	*Porosity, percent*	*Void ratio, e*	D_r,[b] *percent*	ϕ_{TR},[c] *deg*	ϕ_{PL},[d] *deg*
Soft	0.15	47	0.89	30	38	36
Firm	0.76 to 1.35	39 to 43	0.64 to 0.75	48 to 63	39.5 to 42	37 to 38.5

[a] G = penetration resistance gradient.

[b] D_r = relative density = $(e_{max} - e)/(e_{max} - e_{min})$, based on standard American Society for Testing Materials methods.

[c] ϕ_{TR} = angle of internal friction, based on triaxial compression tests.

[d] ϕ_{PL} = angle of internal friction, based on in-place plate shear tests.

Figure 6:

Measured Energy Consumption of the Apollo LRV as Compared to Predicted Values Based on the Soil Properties Indicated (from Ref. 45)

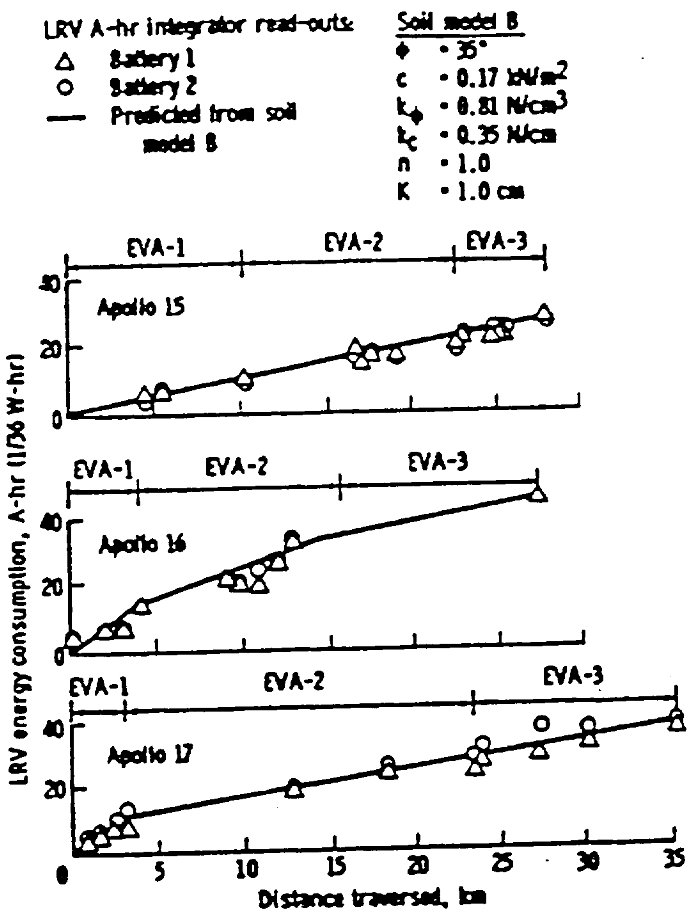


Table 3:

Early Effects of Acute Radiation Exposure

PHYSIOLOGICAL EFFECT	EFFECTIVE DOSE IN REM ABSORBED IN 1 DAY OR LESS FOR 10, 50, OR 90 % OF A POPULATION OF NORMAL PEOPLE TO HAVE THE INDICATED EFFECT		
	10 % EFFECTED	50 % EFFECTED	90 % EFFECTED
Anorexia	40	100	240
Nausea	50	170	320
Vomiting	60	215	380
Diarrhea	90	240	390
Death (20-60 days)	220	285	350

* Exposure for a duration of 1 day or less to blood forming organs (greater than or or equal to 5 cm tissue depth)

** Table was created from SCC 86-02 from Severn Communications Corporation

Table 4:

Summary of Clinical Symptoms of Radiation Sickness

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Time after exposure	Lethal dose (600 r)	Median lethal dose (400 r)	Moderate dose (300–100 r)
First week	Nausea and vomiting after 1–2 hours. No definite symptoms. Diarrhoea. Vomiting. Inflammation of mouth and throat.	Nausea and vomiting after 1–2 hours. No definite symptoms.	No definite symptoms.
Second week	Fever. Rapid emaciation. Death. (Mortality probably 100 percent.)	Beginning epilation.	
Third week		Loss of appetite and general malaise. Fever. Severe inflammation of mouth and throat.	Epilation. Loss of appetite and general malaise. Sore throat.
Fourth week		Pallor. Petechiae, diarrhoea, and nosebleeds.	Pallor. Petechiae. Diarrhoea. Moderate emaciation.
		Rapid emaciation. Death. (Mortality probably 50 percent.)	(Recovery likely unless complicated by poor previous health or superimposed injuries or infections.)

Table 5:

Potential Mobile Surface Applications Payload Equipment

PAYLOAD TYPE	PAYLOAD EQUIPMENT TYPE	MASS (kg)	VOLUME (cm^3)
Surface Sample Collection (LSE-001)	Tongs	1.8	3,181
	Rock Hammer	1.3	1,984
	Rake	1.5	6,000
	Scoop	0.4	141
	Drive Tools	0.9	1,852
	Shallow Drill	22.7	25,017
	Core Tubes	10.8	16,380
	Sample Bags	1.4	182,400
	Sample Boxes	23.6	55,680
	Rock Drill	18.3	3,393
	TOTAL	82.7	296,028
Selenophysical Experiments (LSE-003)	Deep Seismic Arry	25.0	18,750
	Explosive Pkg	584.1	296,000
	Shallow Seis Arry	3.0	1,904
	Thumper	6.0	2,825
	Magnetometer	4.6	11,760
	Gravimeter	5.0	18,000
	Electrical Prop.	10.0	39,157
	Hi Freq Magnetmtr	10.0	18,000
	Solar Wind Exp	6.0	30,380
	TOTAL	653.7	436,786
Selenology Exploration (LSE-006)	Sampling Equip.	63.8	289,186
	Film Cameras	75.0	4,500
	Film	10.0	3,704
	Surveying Equip.	1.4	2,000
	Trenching Tool	1.3	1,125
	Inclinometer	0.3	19,154
	Sun/Gyro-compass	0.5	125
	TOTAL	152.3	319,794

Table 6:

Lunar Surface Transportation Vehicle Functional System Requirements

FUNCTIONAL PERFORMANCE DESCRIPTION	VEHICLE REQUIREMENTS: LOTRAN Req.	LOTRAN Desired	MOSAP Req.	MOSAP Desired	BALTRAN Req.	BALTRAN Desired
Crew Size	4		4		3	5
Max Range from Base (km)	50		500	1500	1500	5464
Max. Total Travel Dist (km)	100		1000	3000	3000	10928
Max. Mission Duration (hrs)	8		336	1000	200	
Gross Payload (kg)	850		2000		1000	
Max. Velocity (km/hr)	15		10	15		
Night Operations Limitations	Within sight of base		None, except drive slower		None	
Pressurized (psia)	No		8-10		8-10	
EVA Events	N/A		12	24	12	
Communications	Contin. Voice & Data		Contin. Voice & Data		Contin. Voice & Data	
Teleoperation/ Automatic Mode		Yes		Yes	Yes	
Remote Manipulator Sys.		1	1		N/A	

3.0 Lunar Rover Trailer

3.1 Chassis and Hitch

3.1.1 Functional Decomposition

The chassis and hitch subsystem is the portion of the vehicle which is responsible for bear the majority of the load of the trailer. These components should provide the strength and structural integrity of the trailer. It its important to note that it is not good enough for these components to bear the required loads without elastic deformation; these components must exhibit negligible strain in order to ensure that their deformation does not interfere with the normal operations of the vehicle, during extreme conditions. The material for the structural members of the trailer is the composite discussed earlier. The components included in this discussion are the frame (chassis), hitch, hitch-to-vehicle attachment device and bed floor.

3.1.2 Proposed Solutions

FRAME (Chassis)

The frame is that portion of the vehicle with will be responsible for providing the rigidity and strength for the trailer. It must support the entire load of the vehicle as well as the pulling force. If designed properly, the frame will also provide degree of damage resistance due impact with large objects such as other vehicles, walls, or sudden, high vertical shifts in the terrain (steep hills, mountains, and craters).

Three types of frames were considered for the trailer. Some of these frame designs have been proven to provide good structural support for vehicles and are commonly used in automobiles and trucks. The three types are the ladder frame, the "X" frame and the "A" frame. Their names give a good idea of their shapes and the figure 7, located in the appendix, will give further illustration. All of the designs being considered

will be good in terms of bearing vertical load. Evaluation will be based upon their resistance to deformation under lateral loads and impact. This includes the ability of the frame to keep its square after a corner impact.

The ladder frame consist of a or a rectangular box with additional structural members going across the center region of the frame. These members provide strength and resistance to damage due to side impacts. However, one disadvantage to using the ladder frame is that it can be knocked out of square by an impact to one of its corners.

The "X" frame is very similar to the ladder frame. It too consists of a rectangular box with additional members in the center. However, these members cross each other, spanning diagonally across the frame. This configuration provides resistance to loss of the frame's square as well as resistance to side impact damage.

The basic shape of the "A" frame is also a rectangle. Its unique feature is the two members which start a the corners of one side of the frame, and end in the center of the other side of the frame. This design provides resistance to the frame loosing its square. However, the "A" frame is the weakest of the three designs being considered, in terms of side impact resistance.

Frame Evaluation
3 = best
2 = median
1 = worst

FRAME	Lateral Strength	Longitud-inal Strength	Ability to Maintain Square	**TOTAL**
ladder	3	1	1	5
"X"	2	2	3	7
"A"	1	3	2	6

table 7.

The frame type selected for the chassis is the "X" frame. This frame provides good lateral and longitudinal strength as providing an excellent means of maintaining square. Specific frame dimensions will be determined by the overall dimensions of the vehicle, the thickness of the members, and the system integration needs between the chassis and other subsystems. A finite element analysis computer program (MSC PAL 2) was used to help determine the cross section of the members, based upon load requirements. A printout of the files and drawings used to do the FEA are located in the appendix. DesignView 3.0 was used to design and help determine the geometric characteristic (lengths, areas, moments of inertia, etc.) of the frame. Figure 8 illustrates the final design of the frame. Modifications to the standard "X" frame design were made in order to accommodate the trailer hitch. This will be discussed in more detail in System Integration.

HITCH

The function of the hitch is to provide the physical connection between the trailer and the vehicle. It also serves as the steering input from the vehicle to the trailer. The hitch should provide at least 4 degrees of freedom. Three of these degrees of freedom should be rotation along the x, y, and z axis. The third degree of rotation should be some degree of translation in the vertical direction to allow for a difference in height between the vehicle and the trailer. The hitch should also be strong enough to endure the loads associated with towing the trailer. Finally, the hitch should provide a means of attachment to the vehicle which does not require major modifications to the vehicle. The attachment should also be easy for the astronauts to manipulate, not too complicated or cumbersome.

A trio of designs were considered for the vehicle hitch. One design was derived from current tractor trailer configurations. It involved a pin-joint between the trailer and the vehicle. Another design was taken from a toy wagon. The wheels are connected to a

pivot and the pivot is connected to one or two joints and finally to the vehicle. The last design is a simple connection of a rod with several types of joints (pin, ball and socket, universal ...) Figure 10 provides an illustration of these alternative solutions.

The tractor trailer configuration provides a design which is strong. However, it will not provide the necessary degrees of freedom to ensure that the trailer will have adequate mobility. Also, the attachment may prove difficult.

The "wagon" hitch operates by placing the wheel support beams on a pivot. The pivot is then connected to the vehicle via a rod with joints in it. Hence, the turning action of the pivot, turns the wheels. Vehicle attachment methods include a removable pin (forming a pin joint), a nut and bolt connection (similar to a cable jack connection), and a hook.

The final type of hitch considered was simply a rod connecting the trailer to the vehicle. The rod would have several joints in it to provide the necessary degrees of freedom. Several types of vehicle attachments are available as with the wagon.

Hitch Evaluation Table
3- good
2 fair
1 poor

HITCH TYPE	d.o.f.	Strength	Attach-ment Ease	Steering Input	**TOTAL**
truck hitch	3	3	1	1	8
toy wagon hitch	2	2	3	2	9
rod	1	1	3	1	6

table 8.

From the evaluation chart it is clear that the type of hitch chosen was the toy

wagon style The hitch was designed with the aid of MSC PAL2 and DesignView 3.0. Documentation of the programs and drawings used to create the design are given in the Appendix. The final design can be seen in figure 12. Note that a ball and socket joint and a pin joint are present. The ball and socket joint is present to ensure that adequate rotation is provided. The bearings for the pivot are self lubricating, decreasing the need for maintenance. An additional joint of at least 1 degree of freedom of rotation was also needed to provide for vertical translation. The selection of a pin joint was the result of selection and system integration processes which will be discussed in the next sections.

Trailer-Vehicle Attachment

The selection of the toy wagon style of hitch leaves the connection of trailer hitch design open. As mentioned previously, there are a variety of choices available. Trailer-vehicle connections which were considered were pin joints, nut and bolt connections and a hook. The criteria used to evaluate these options were strength, attachment ease and effect of the design (modifications) of the vehicle. Figure 16 contains illustrations of the attachment alternative being discussed.

The pin joint is a simple and proven method of attachment which provides one degree of freedom. The attachment would require the astronauts to position the hitch where a pin could be placed through vehicle's portion of the joint, and the hitch.

The nut bolt connection involves having a nut fixed to the hitch. It would be allowed to rotate and translate horizontally over a fixed length. nut would mate with a bolt on the vehicle. The astronauts would rotate the nut until it was snuggly connected to the vehicle.

The hook design entails a hook which would hook into a loop. The shape of the hook would prevent an unwanted disconnection of the vehicle and trailer.

Attachment Design Evaluation
3 - good
2 - fair
1 - poor

ATTACH - MENT METH- OD	Strength	Attach- ment Ease	Vehicle Modifi- cation Require- ments	Attach- ment Relia- bility	TOTAL
pin joint	2	3	3	3	11
nut- bolt	1	1	2	2	6
hook	2	3	3	1	9

table 9.

The method selected was the pin joint. Calculations were done to determine the specific dimensions necessary to ensure the pin joint is strong enough. The calculations are located in the appendix. A detailed drawing of the final attachment design is given in figure 17.

3.1.3 System Integration

It is important to note that the design of the frame and hitch system components was done simultaneously. The goal and effect of this was to allow for smooth system integration between the components. The frame design had to be modified to provide support for the hitch (see figure 15). As mentioned before, extra members were added to the "X" frame for this purpose. Also, the hitch and frame had to be designed so that deformation due to loads, did not result in interferences of the hitch movement. Therefore, it was the degree of elastic strain and not the occurrence of plastic strain that became the critical concern of the hitch and frame design.

The design of the attachment method was driven by the hitch method selection. The chosen hitch required that the attachment method allow for one degree of freedom. Hence, while the attachment was design as a separate component from the hitch, it is

itself, part of the hitch.

3.2 BODY

DESIGN OF LUNAR ROVER TRAILER BODY

The main mission requirement for this Lunar Rover Trailer is to aid in the exploration of the surface of the moon. It performs this task by functioning as a transportation system implemented to move astronauts and cargo. To explore the surface of the moon a variety of equipment and materials will be needed and various amounts of samples taken. Cargo, with regard to this trailer design, is defined as samples, which consists of rocks and sand, mining equipment, which consists of picks, shovels, and explosives, and personnel and equipment which consists of astronauts and their support equipment. The body of the lunar trailer must be capable of supporting and containing its cargo safely, securely, and without disruption from storage, transportation, and the environment. Three alternative design solutions where developed for the body of the Lunar Rover Trailer: the Storage Bin Design, the Flat-Platform design, and the Storage Container Design.

3.2.1 Proposed Solutions

The Storage Bin Design: This design designates the storage area of the trailer as a large rectangular container. The cargo would be contained within the trailer by retaining walls of the trailer body. Different cargo would be separate from each other by placing it in individual storage bags. These storage bags would be made out of a fabric (made out of a composite) and be capable of containing samples, mining equipment, and personnel equipment. Inside the container area is the seating area, it is comprised of a bench attached to the trailer body which would have the length and the width to seat two astronauts in full space suits. On three sides of the bench would be retaining walls to enclose the astronauts for transportation.

The Flat-Platform Design: In this design the body of the trailer would be flat platform. On the surface of the platform would be connectors that would allow components to be attached to it. The design would require four large bend or container components all with equal volume and storage capacity. These containers would be able to be secured and removed to the surface of the trailer in an area in the rear which would be designated the storage area. All the containers would be open for easy access and the interior of each container could be specially customized to store a certain type of cargo. In the front of the trailer would be the seating area where seat or bench could be attached. The bench would be large enough so that two astronauts can be seat on the bench in full space suits. The bench and the container connectors would be compatible with one another so that a containers could be placed in the seating area and the bench could be place in the storage area. The body of the trailer would be capable of housing six containers or four containers and the seating bench in different configurations.

The Storage Container Design: In this design the body would be comprised of two main parts, the seating area and the storage area. The storage area would be located in the rear of the body and house four storage containers and each storage container would be capable of holding about .424 m^3 (14.96 ft^3). The containers would have lids to secure the cargo placed in them. In the front of the trailer there would be the seating area where two astronauts can be seated for transportation. On each side of the astronauts would be a storage compartment where they can place personnel equipment. There would be access ways to the storage containers and to the seating area making them accessible to the astronauts. There would also be a ladder located on each side of the trailer near the seating area where the astronauts could gain access to the trailer. The seating area would be enclosed by a retaining wall (which would be high than the astronaut head when seated) to protect him from the dust the would be projected into the lunar atmosphere by the Lunar Rover Trailer and Vehicle.

3.2.2 Functional Decomposition

The Storage Bin Design. The design of this trailer requires the base of the trailer body to be about 4 feet above the ground. At this height placing the storage bags in the storage area of the trailer body would be difficult. As the trailer moves across the lunar surface the bags would shift and to secure them to prevent shifting would make loading more difficult. The bags would not be easily accessible and would not be ideal for storing picks and explosives. Based on these reasons this design alternative was rejected.

The Flat-platform Design: This design alternative was rejected because of the following reasons. With the base of the trailer body about 4 feet from the ground, the connecting of loaded containers to the trailer body from the ground would be very difficult. The cargo and the astronauts would not be protected from the lunar environment. The cargo would not be secure if the are no lids or covers on the containers.

The Storage Container Design: This design alternative was accepted because it best met the requirements of the lunar trailer. The cargo would be contained in their own storage container with lids to secure them. The access ways on the trailer body will make the containers accessible. The retaining walls would protect the astronauts and the cargo from the environment of the lunar surface. The Storage Container Design. The trailer body will be place (attached) on the fame of the trailer and the entire body will be made from a carbon graphite composite material and cover about 8.14 square meters.

3.2.3 Proposed Subsystems and Evaluation

Containers:

The containers will have a volume of .424 m^3 each. The containers will have a retaining wall .75 meters high, but will only be .5 meters deep so that they will be more accessible for the astronauts. The lids on the containers are also made of the carbon graphite composite and slide open and closed. The containers and their doors are

specially molded (casted) to work this way, and the lids will be able to lock and unlock. The storage compartments on the astronauts bench are cut into the bench itself and half no containing doors.

Access Way:

The access way is about .652 meters wide and runs the width (near the seating area) and the length (between the storage containers) of the trailer. The access way makes the seating area and the storage containers accessible to the astronauts. The is a latter which (located in the seating area) which gives access to the trailer. The latter must be moved into and out of position from outside of the trailer.

Thickness:

The is a retaining wall around the storage area of the trailer which is about .75 meters high and about 1 meter high around the seating area. The retaining wall, container wall, and trailer body thickness is about 3 inches thick, so it can support the load of its cargo. This is based on the strength of the carbon composite and the maximum weight of the cargo.

Exploration of Lunar Surface:

To accomplish its mission of exploration the lunar rover will be required to transport a variety of equipment and cargo. We have determined that the trailer will have three transportation functions: the transportation of Samples, including sand and rocks; Mining equipment, including picks, shovels, and Explosives; and Personnel & Equipment, including astronauts and personnel life support. Each of the four containers are identical and can be customized to storage whatever cargo is required. The designation of what cargo goes into what container can be determined by the astronauts (or mission control.) See figure 18 for a detailed drawing.

3.2.4 System Integration

Before analyzing the specific design problem of the Lunar Rover Trailer, the

problem of transporting the trailer to the moon must be addressed. It would be possible to utilize any heavy lift launcher with the payload capacity of 393 m3 to transport the trailer. The launcher should have capability of delivering the required payload to the surface of the moon and the vehicle is to support lunar base operations in the year 2000. The wheel design was based on the vehicle's weight and performance requirements. Each wheel is designed with the same characteristics and the therefore can be optimized of the vehicle as a whole. The wheel is of a size and form which does not intefere with the other functions of the trailer.

3.3 SUSPENSION AND WHEELS

The object of wheel suspension is to transform sharp jolts from an uneven road bed surface to soft damped oscillations. As a result only small forces are transmitted to the body. The manner in which this is accomplished is to provide a system that when a force is applied to it will resist the force and provide a reaction force that is a smooth transition back to the original position of the system. Systems currently being used for wheel suspension are the leaf spring, the coil spring, and the torsion bar.

A short bar loaded in pure compression by a force P acting along the centroidal axis will shorten in accordance with Hooke's law, until the stress reaches the elastic limit of the material. At this point, permanent set is introduced and usefulness as a machine member may be at an end. If the force P is increased still more, the material either becomes "barrel-like" or fractures. When there is eccentricity in the loading, the elastic limit is encountered at small loads. The basic wheel suspension designs will follow the principles of a short bar and the operation of them can be explained as followed.

Assume the strut is analogous to the bar pictured below.(FIG) The compressive stress in the x direction at point D in an intermediate section is the sum of a simple component P/A and a flexural component My/I i.e. : $sc = P/A + My/I = P/A + PeyA/IA = P/A(1+ey/k^2)$ where $k = (I/A)^{1/2}$ and is the radius of gyration, y is the coordinate of

point D, and e is the eccentricity of loading. The y coordinate of a line parallel to the x axis along which the normal stress is zero is found by setting $s_C = 0$ and solving for y.

Several analysis have been performed by the manufacturers of wheel suspensions and the assumptions of the best suspension for the lunar rover trailer are taken from the results of the test performed by the manufacturers.

3.3.1 Proposed Solutions

Leaf springs (FIG) are the oldest type of suspension. They consist of stacks of steel strips held together by clips.

Coil springs (FIG) are widely used because they are lighter than leaf springs and require less maintenance. However, they do not have the oscillation damping characteristics of leaf springs

Torsion bars (FIG) utilize the frame by fixing one end of the bar to the frame while the other is connected to a lever arm.

3.3.2 Functional Decomposition

The suspension system chosen for the trailer was chosen based on the need of increasing the load that the trailer can carry, providing a stable ride across the lunar terrain, and minimizing the added weight of the system to the overall vehicle. To accomplish the goals, the springs were evaluated on the maximum load capabilities, strength to weight ratio and smoothness of oscillations produced. The system used for evaluation is the 1-3 point scale where 1 is the least desirable of the components.

SUSPENSION	MAX LOAD	STRENGTH/WEIGHT	SMOOTH OSCILLATIONS

leaf spring	3	1	3
coil spring	2	3	1
torsion bar	1	2	2

The leaf spring with its maximum load capabilities and smooth oscillations would be a superior spring but it has a draw back in its weight. Due to the nature of the leaf spring design , the weight of the spring is high. In considering the design the weight is a factor that is addressed. In order to limit the weight one might choose the second best spring design, but the max load capabilities are sacrificed when the coil is used. A viable alternative is to use a combination of the two springs. For instance; if an area of the trailer could withstand a lighter spring the will not carry as much load, the coil spring could be utilized in this region. Likewise, if the area of the trailer that carried the maximum load utilized the leaf spring then the requirements of both load capabilities and weight consideration are met. As is the nature of the suspension system, the smooth oscillations will be met with the use of any of the suspensions mentioned.

In the design of the trailer, the front suspension chosen was the coil spring. In the rear where the maximum load is carried, the leaf springs will be used. This design will meet our requirements as set forth above, the maximum load will be increased by the use of the leaf springs, the smooth oscillations will be accomplished by maximizing the suspension ability of the given systems, and the minimalization of added weight will be accomplished by the use of two type suspension systems.

3.3.3 Proposed Subsystems and Evaluations

Suggestions for the suspension include a thorough and often check of the suspension. Due to the unique conditions on the surface of the moon, i.e. the radiation and temperature characteristics, it is recommended that the suspension be changed on a regular basis to maintain proper operation of the system.

Mobility of the vehicle can be stated as the ability of the trailer to move around the lunar surface. The mobility of the vehicle is very important to the defined mission and thus much effort was made to evaluate good alternatives for mobility systems. The movement around the surface can be accomplished by three basic systems: tracks, walkers, or wheels.

Tracked vehicles outperform wheeled vehicles in soft soil and with large payloads. The performance characteristics of tracks are determined by the large track contact area. Large contact area means excellent flotation characteristics, large draw bar pull values, and a high degree of motion resistance (this implies energy loss and power use).

Tracks are used on earth when their large footprint area is needed in soft soil. Considering the low lunar gravity, however, such soil strength would have to be very low by terrestrial standards. Tracks used for earth applications have very poor wear characteristics. There is a high frequency of breakdown and tracks are only made practical by making them big, heavy and sturdy. In addition, large military tracked vehicles must normally be transported on wheeled trailers to move long distances.

Walkers(FIG) are currently being researched extensively. At present ,however, walkers are very complicated and in efficient vehicles. Walkers are plagued by large dynamic loads, non-uniform motion, and a vehicle geometry that must follow the random geometry of the terrain. walkers are inefficient in their use of energy. A walker taking short steps spends much of its energy moving the cg of the vehicle up and down.

Wheels (FIG) have proved to be excellent mobility choice for past lunar mobility systems. The MET (modular Equipment Transport) used in Apollo 14, the LRV used in Apollo 15-17, and the Soviet Lunokhod have all demonstrated the wide range of wheeled vehicle options. The MET was a two wheeled ricksaw type vehicle with pressurized tires. The LRV was a four wheeled vehicle driven by astronauts. Its wheels were flexible wire mesh with chevron shaped treads. The Lunokhod had eight rigid wheels.

Wheels have tremendous versatility. There is a large range of wheel types, sizes,

numbers, and configurations. While rigid wheels and pneumatic tires have proven not well suited for many lunar applications, many types are suited. These include: wire mesh, metal-elastic, elliptical, hemispherical, and cone wheels.

The criteria for selection of the mobility system are lightweight(lw), sturdy(s), dependability(d),proven history(ph). The point system is 1-3 with 1 being the least desirable and a 0 applied to any parameter not currently known.(such as no walkers on the moon ph=0)

SYSTEM	LW	S	D	PH	TOTAL
tracks	1	3	2	0	6
walker	2	2	1	0	5
tires	3	2	3	3	11

It is clearly shown that the wheel is a superior choice for the design of the mobility system. The tracks and walkers may serve a lunar purpose, but they will not be useful here.

3.3.4 System Integration

The design of a wheeled vehicle system is a complicated science. While required ground contact area can be calculated fairly easily, there is an almost infinite combination of wheel sizes, geometries, numbers, and configurations that can meet a contact area specification. More smaller wheels have more redundancy and better reliability. fewer larger wheels tend to be mechanically simpler and weigh less. The choice made is with the fewer larger wheels both for the simpler mechanics and the lighter weight. The material chosen is a matrix composite. This will allow the wheels to withstand the environment of the lunar surface. The shape of the wheels is the experimental hemispherical shape. This shape will allow for the large amount of surface area to be in

contact with the ground which will aid in the reduction of sinkage of the vehicle as it travels across the terrain.

The wheels are the choice to meet the requirements set before. They are lightweight, sturdy dependable and they have a proven history. This makes the wheel the best choice to accomplish the task.

Suggestions for the wheel include the monitoring of the performance of the wheel since it is experimental. The material chosen is suitable for the application, but as new technology arises, other materials can be substituted.

3.4 Manufacturability

The lunar rover trailer proposed in this design project is to be used specifically for space exploration on the moon. It consist of composite materials that are lightweight, strong, and durable under the environmental conditions on the moon.

Composite materials are considered to be very expensive to manufacture. This design will utilize composite components that are meshed together with a singular component to eliminate a vast majority of bonding or welding joints. The creation of a minimum number of composite components will be beneficial in eliminating the stresses that occur when joining structures together. The materials and components utilized in this design meet the standards set by NASA for lunar transportation and operation on the lunar surface.

4.0 Results

The designed lunar rover trailer for this project meets the desired objectives. The body and frame were designed to withstand a maximum cargo load of 7,000 kg. This will allow for a facto of safety of 6.0. This lunar rover trailer incorporates a suspension system that overcomes 0.75 meter obstacles during lunar operations. The suspension as well as the hitch design allow for a climbing angle of 53°. The total hitch assembly is designed to handle a maximum towing capacity of 60,000 N. The overall trailer dimensions and weight allow for the trailer to be transported to the moon in the shuttle cargo bay or any other heavy lift vehicle. Also the trailer is self-supporting and contains a six-wheel suspension system. The weight of the trailer is approximately 5,000 kg. Most importantly, due to the material selection for this trailer, it is capable of being operated during both lunar days and nights. See figure 21 for a detailed illustration of the overall design.

5.0 Conclusions

The trailer designed can serve in a number of capacities. Its body design allows for the transportation of several types of cargo. The storage compartments close allowing for the secure transportation of sand, rocks, and mining equipment. The front of the trailer provides seating for astronauts. The trailers ability to turn makes it highly maneuverable. Its combination of coil and leaf- spring suspension, at the rear wheels pivot design, creates a smooth and stable ride over the rugged lunar terrain.

It is expected that 25 years advance in technology will provide a lunar vehicle which will be able to tow the trailer. The trailer design is such that it should be able to traverse any terrain the which does not restrict the vehicle. Lunar terrain will limit the speed of both the vehicle and the trailer eliminating concerns over high speed performance. The results of the design is a vehicle which is durable and highly functional and will prove an asset on many types of lunar expeditions.

6.0 Appendices

6.1 Appendix A: Figures

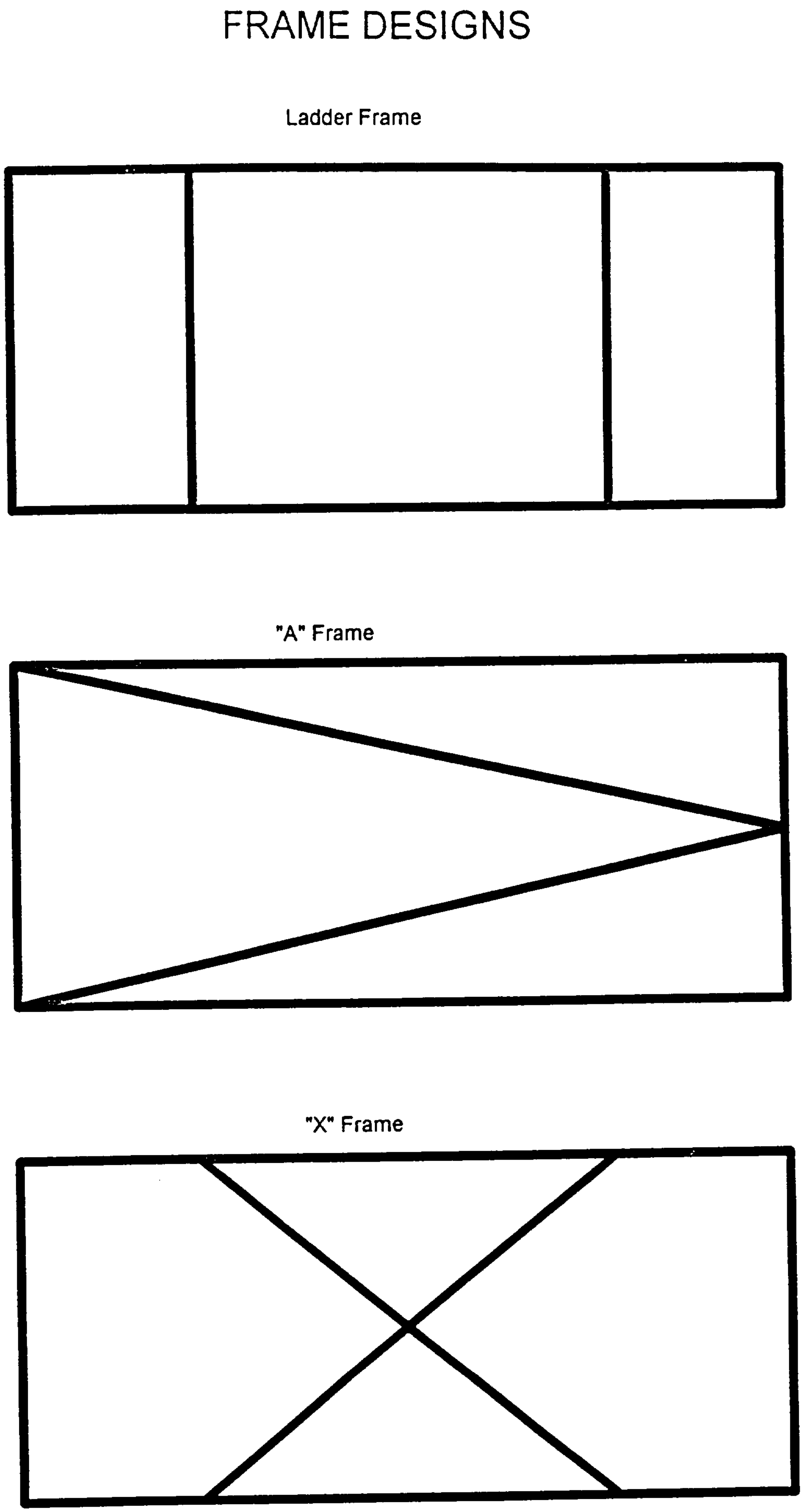


Figure 7

TOP VIEW
FRAME

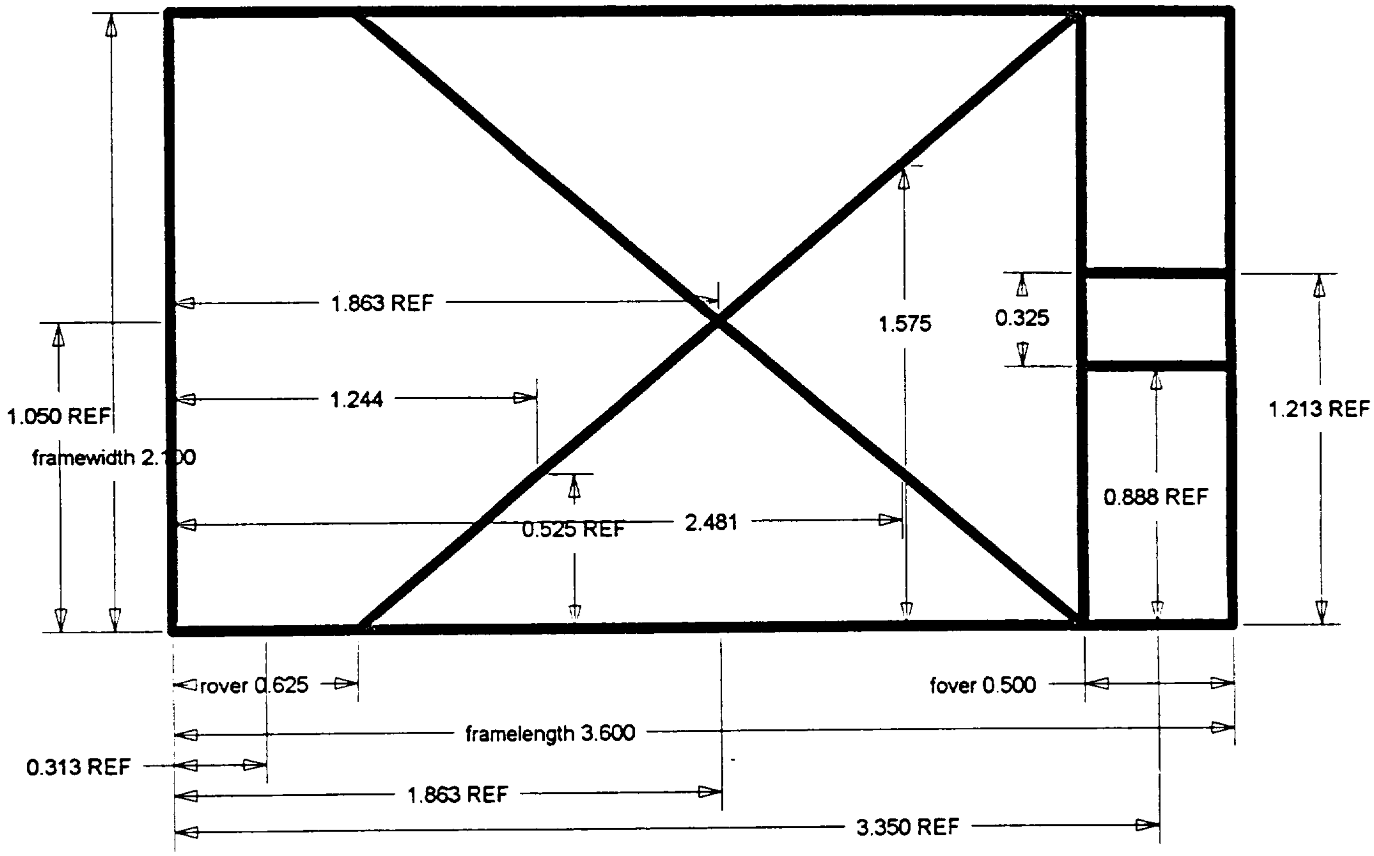


Figure 8

CROSS SECTION VIEW
I - BEAM

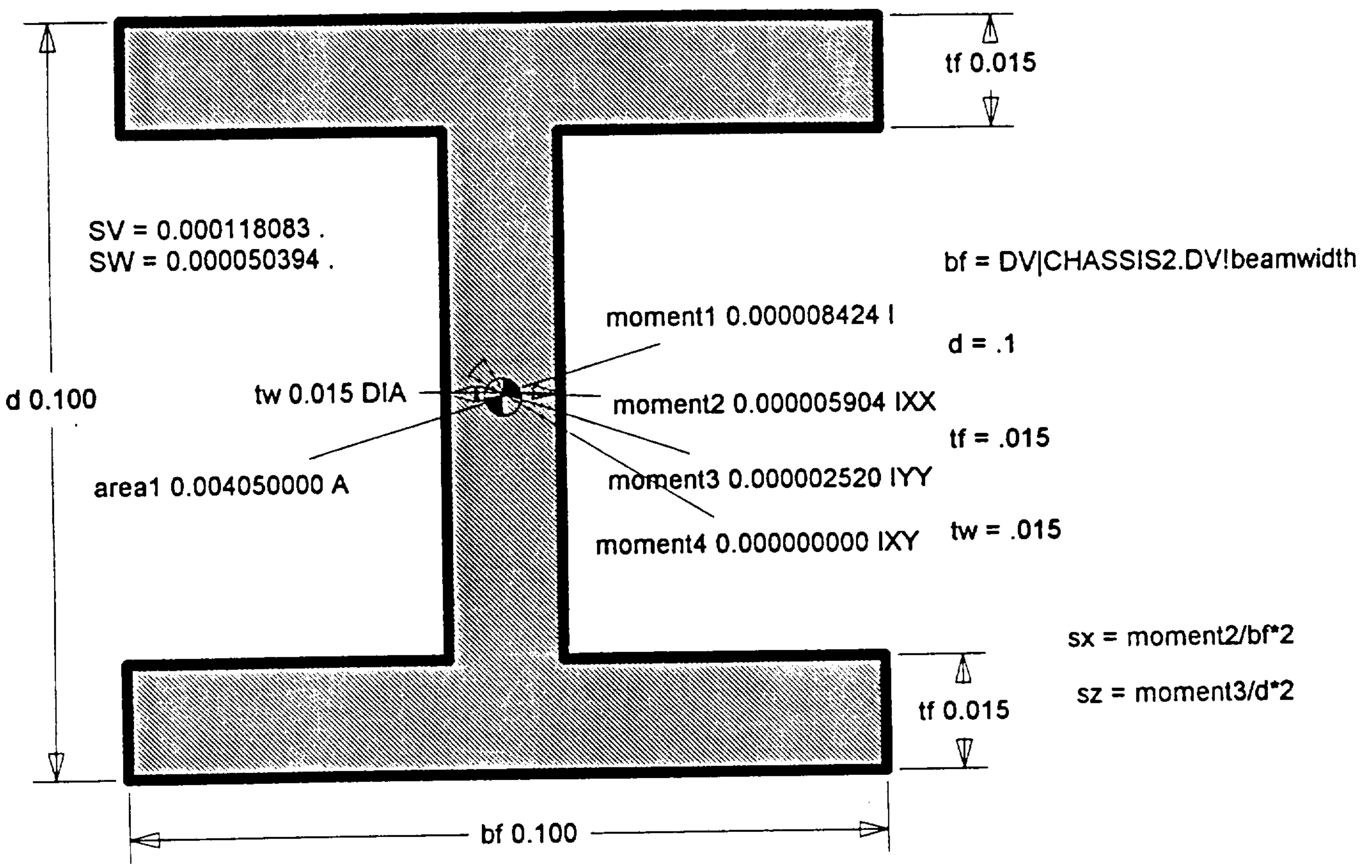
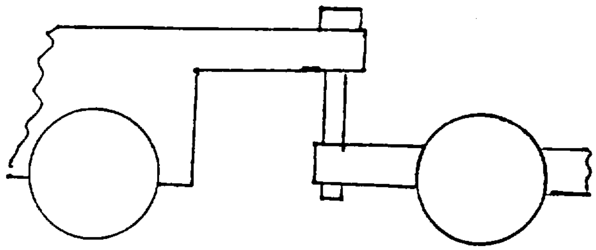
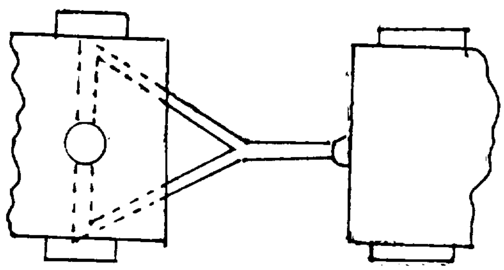


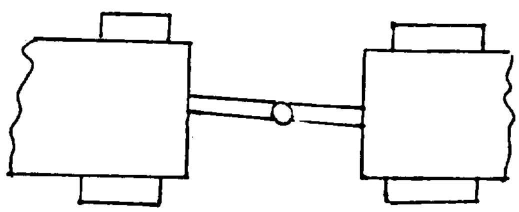
Figure 9



Truck style hitch

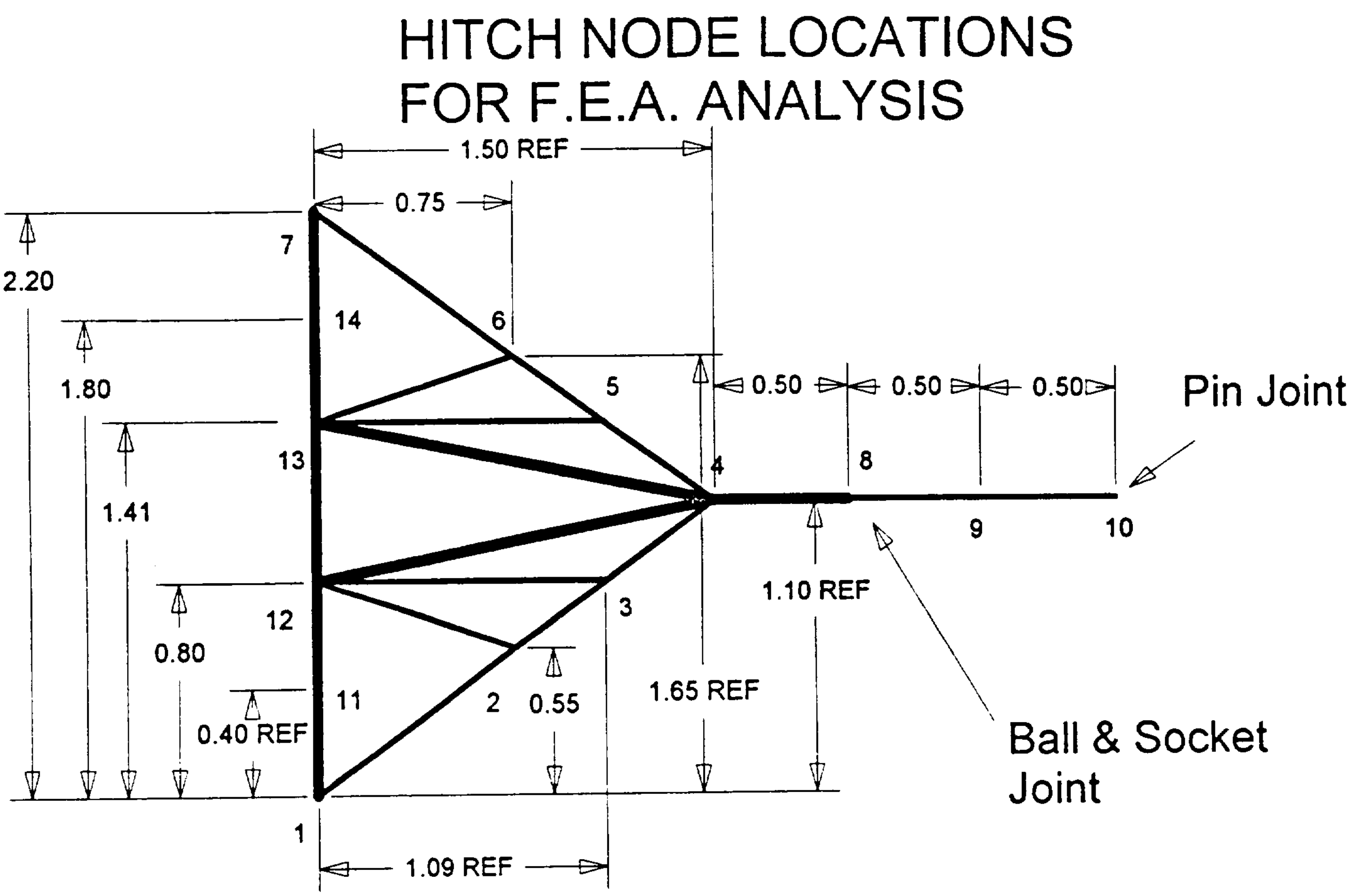


Wagon hitch



Rod style hitch

Figure 10



HITCH NODE LOCATIONS
FOR F.E.A. ANALYSIS
1.50 REF
0.75
2.20
7
14
6
1.80
5
0.50
0.50
0.50
Pin Joint
1.41
13
4
8
9
10
1.10 REF
12
3
0.80
11
2
0.55
1.65 REF
0.40 REF
Ball & Socket
Joint
1
1.09 REF

Figure 11

HITCH

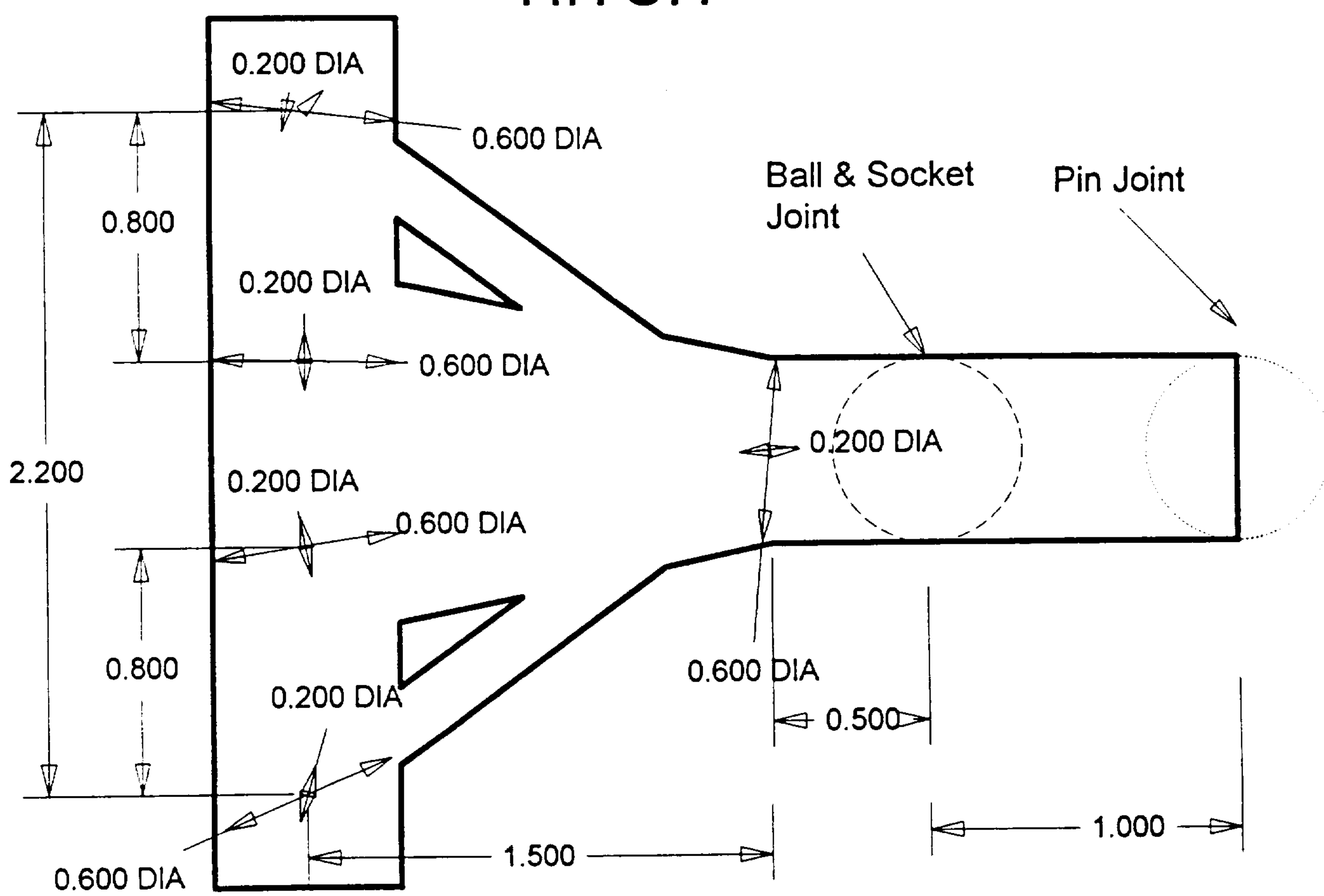


Figure 12

CROSS SECTION VIEW
I - BEAM

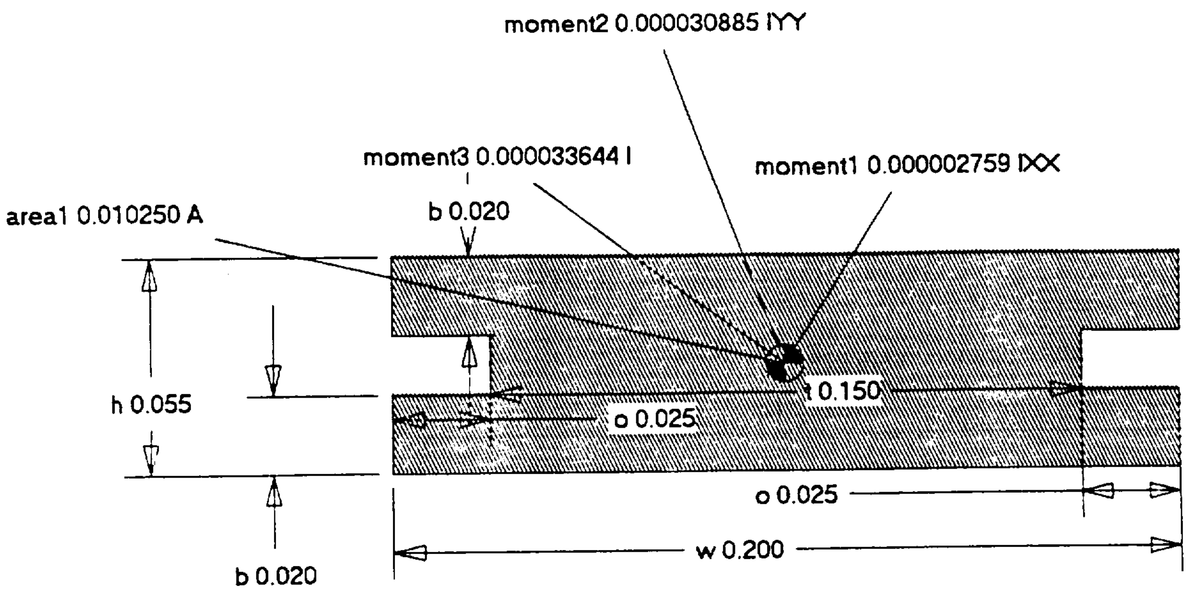


Figure 13

Hitch Beam Cross Section

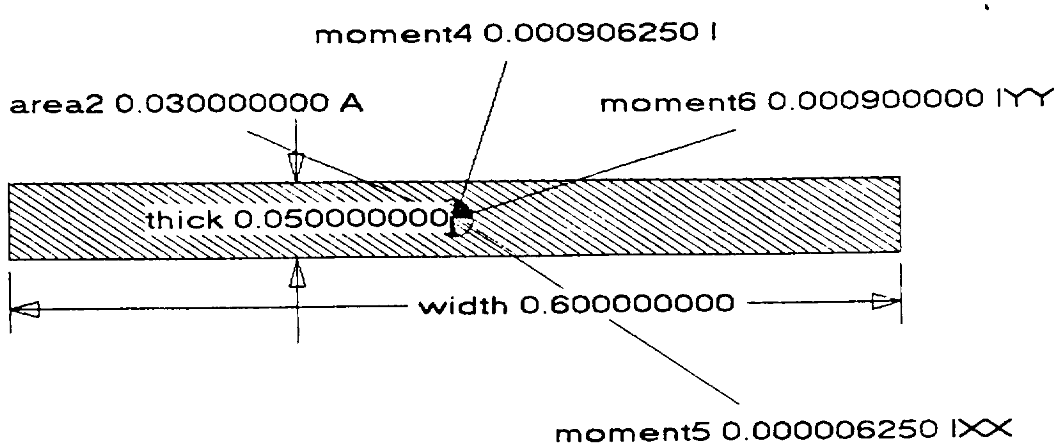


figure 14.

TOP VIEW
HITCH AND FRAME

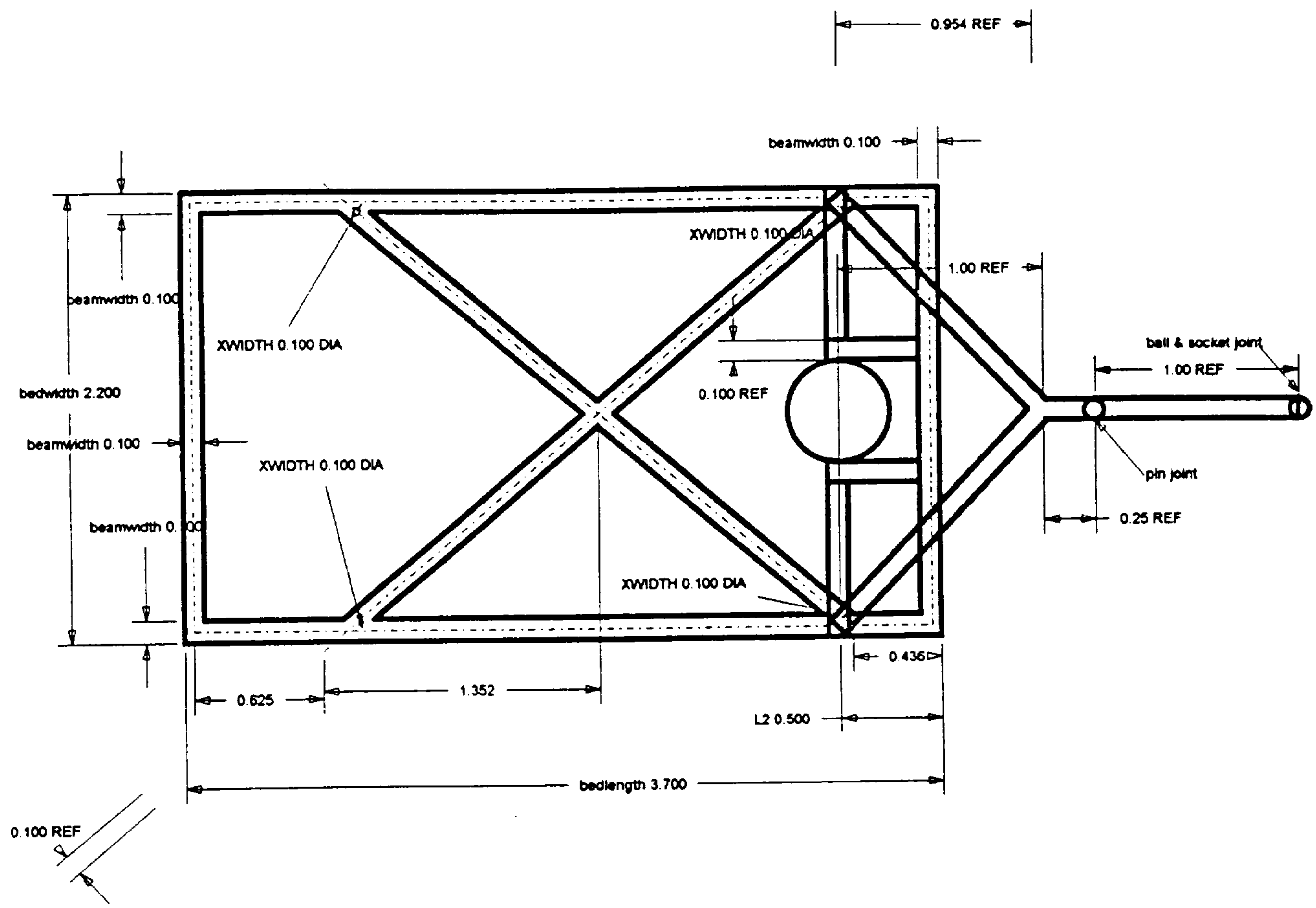


Figure 15

HITCH TO VEHICLE
ATTACHMENT ALTERNATIVES

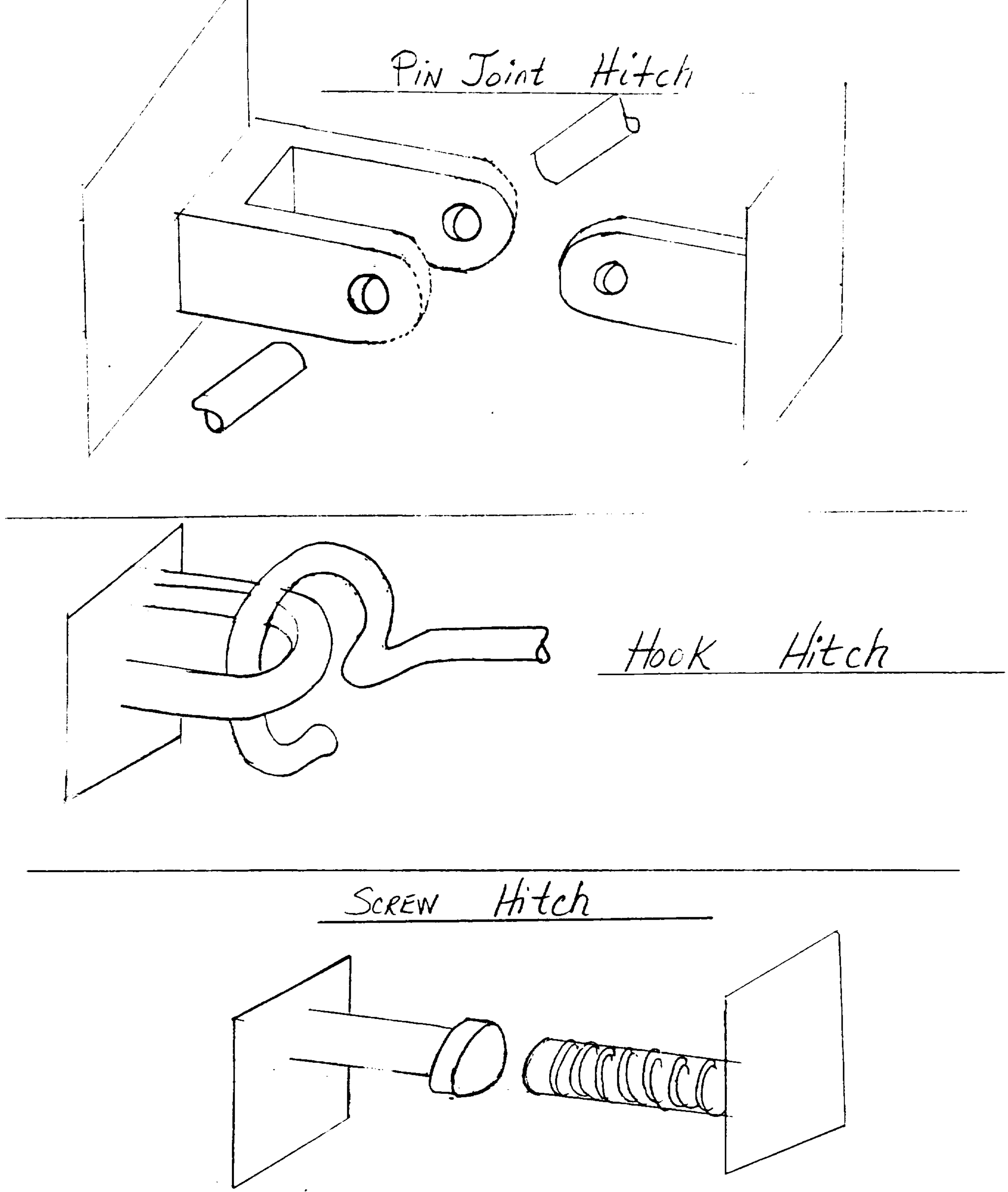


Figure 16

HITCH TO VEHICLE
ATTACHMENT

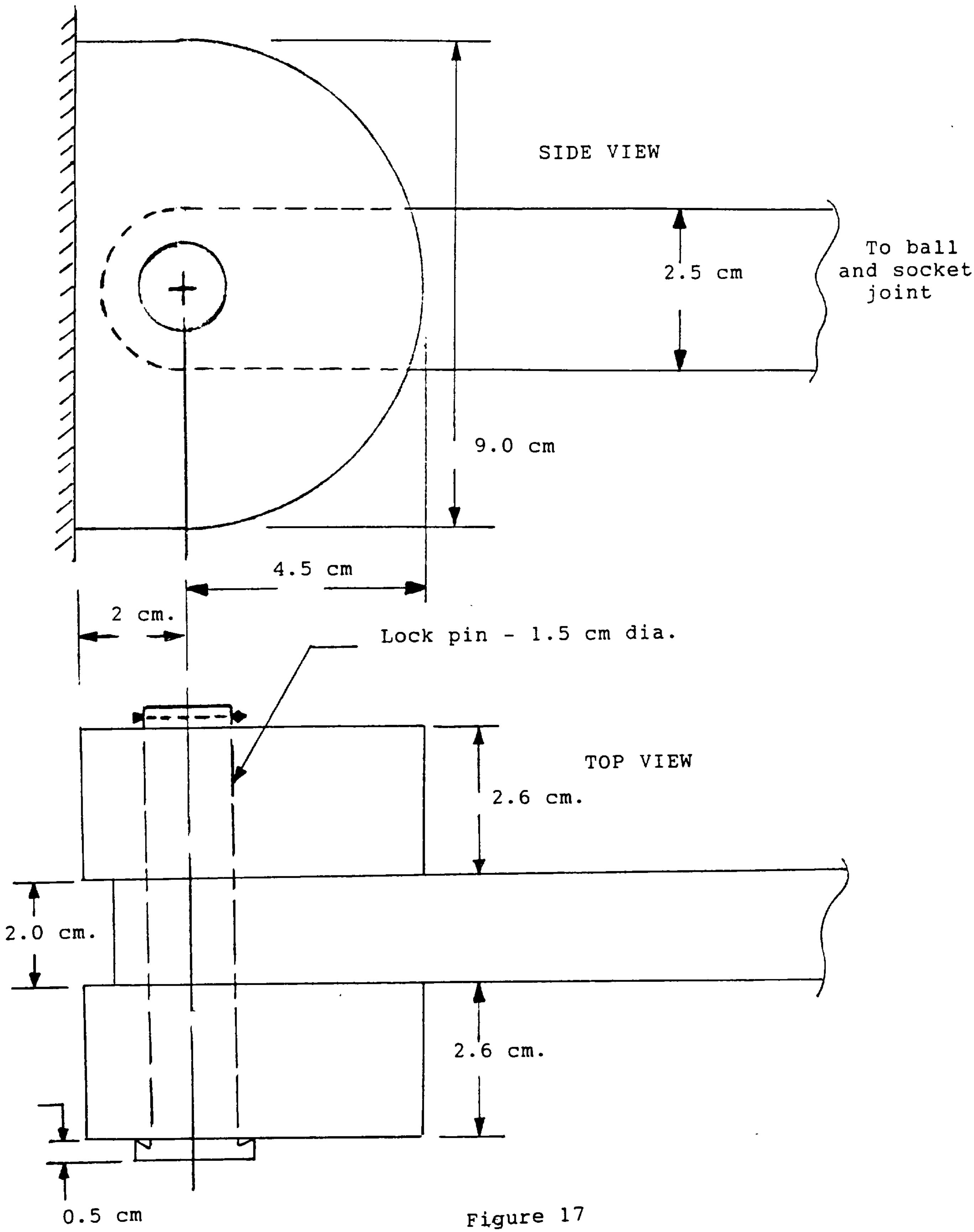
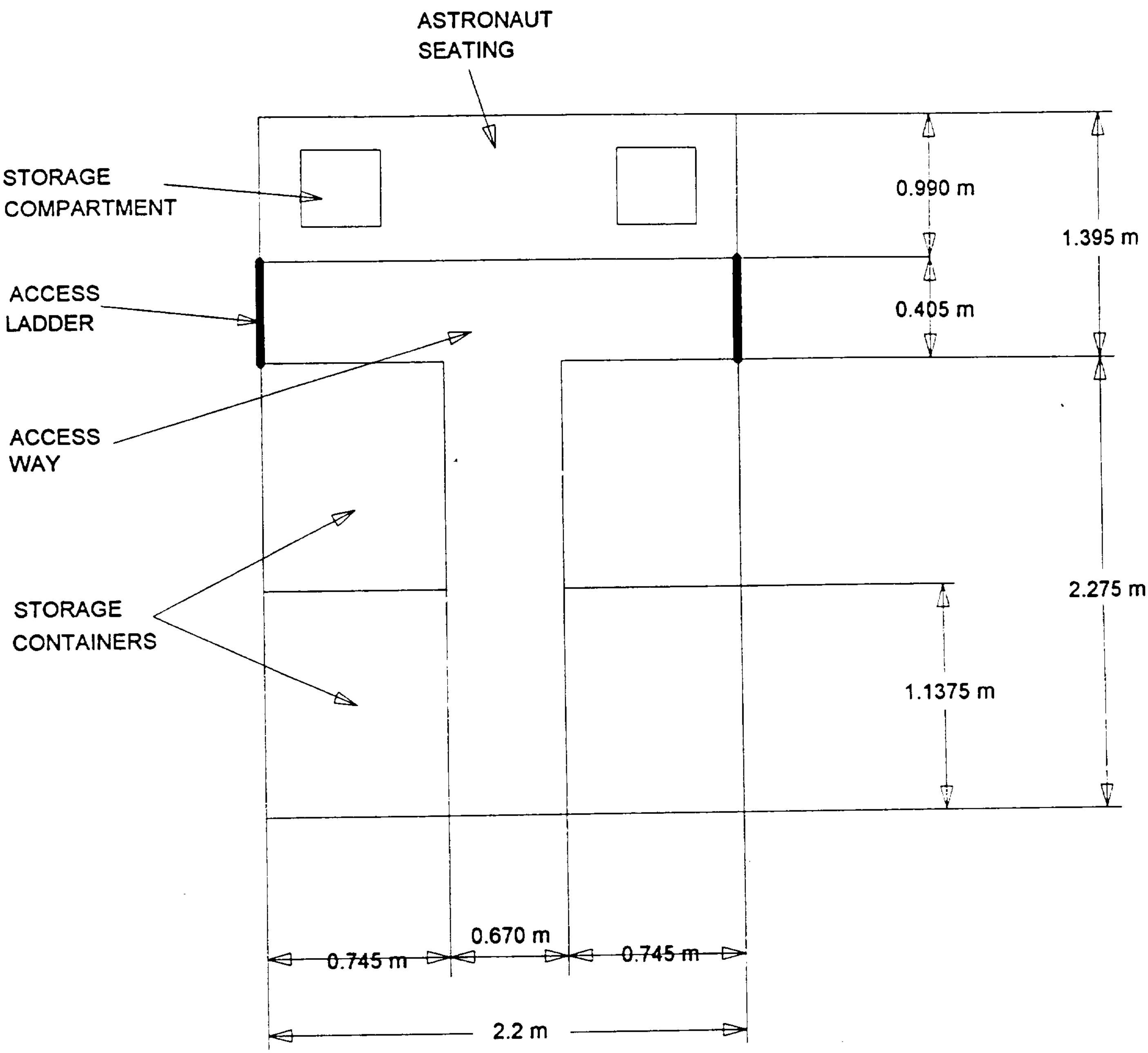


Figure 17

BODY OF TRAILER

TOP VIEW



* Retaining Wall thickness for whole trailer body is 1 cm.

Figure 18

FRONT SUSPENSION

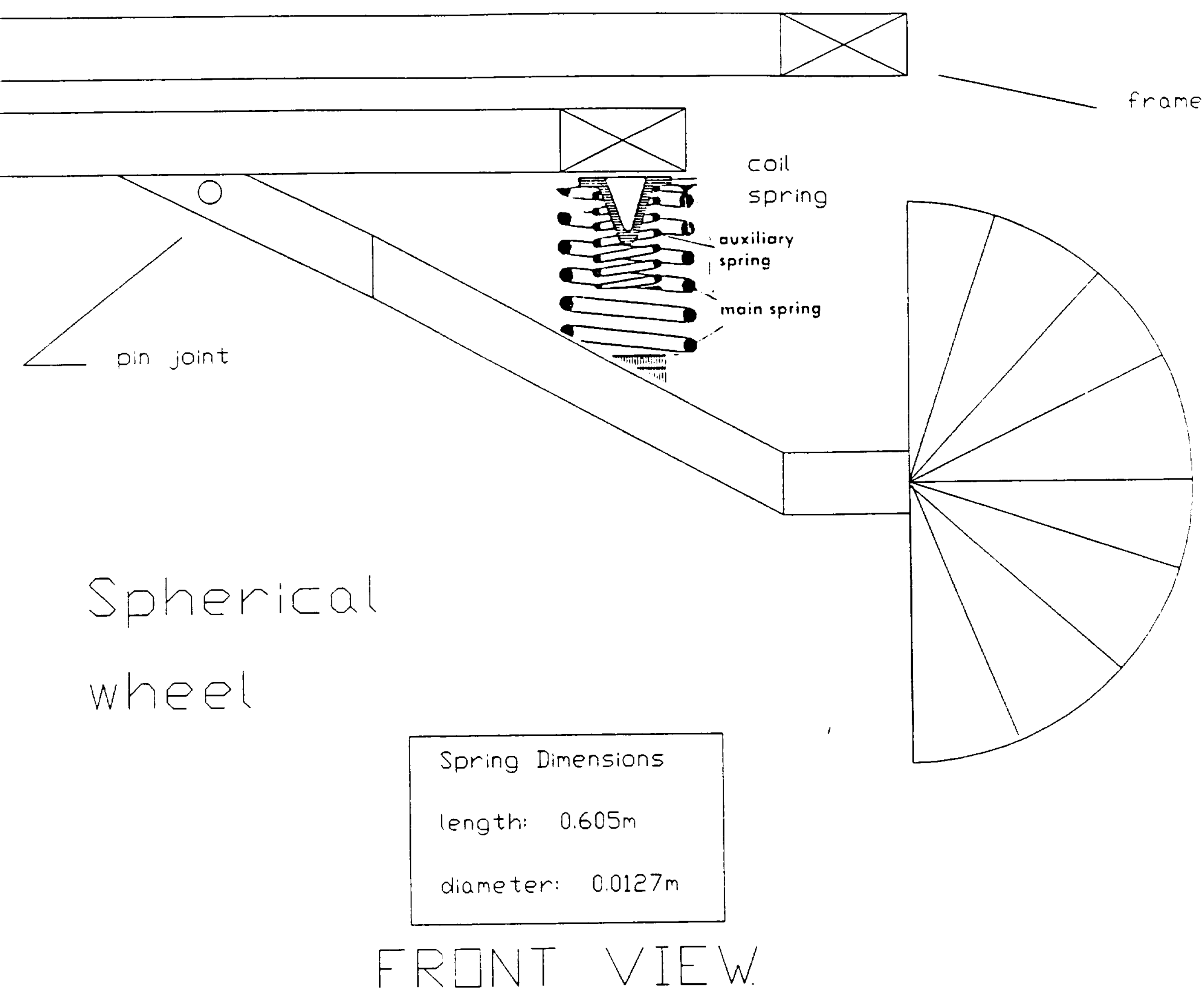
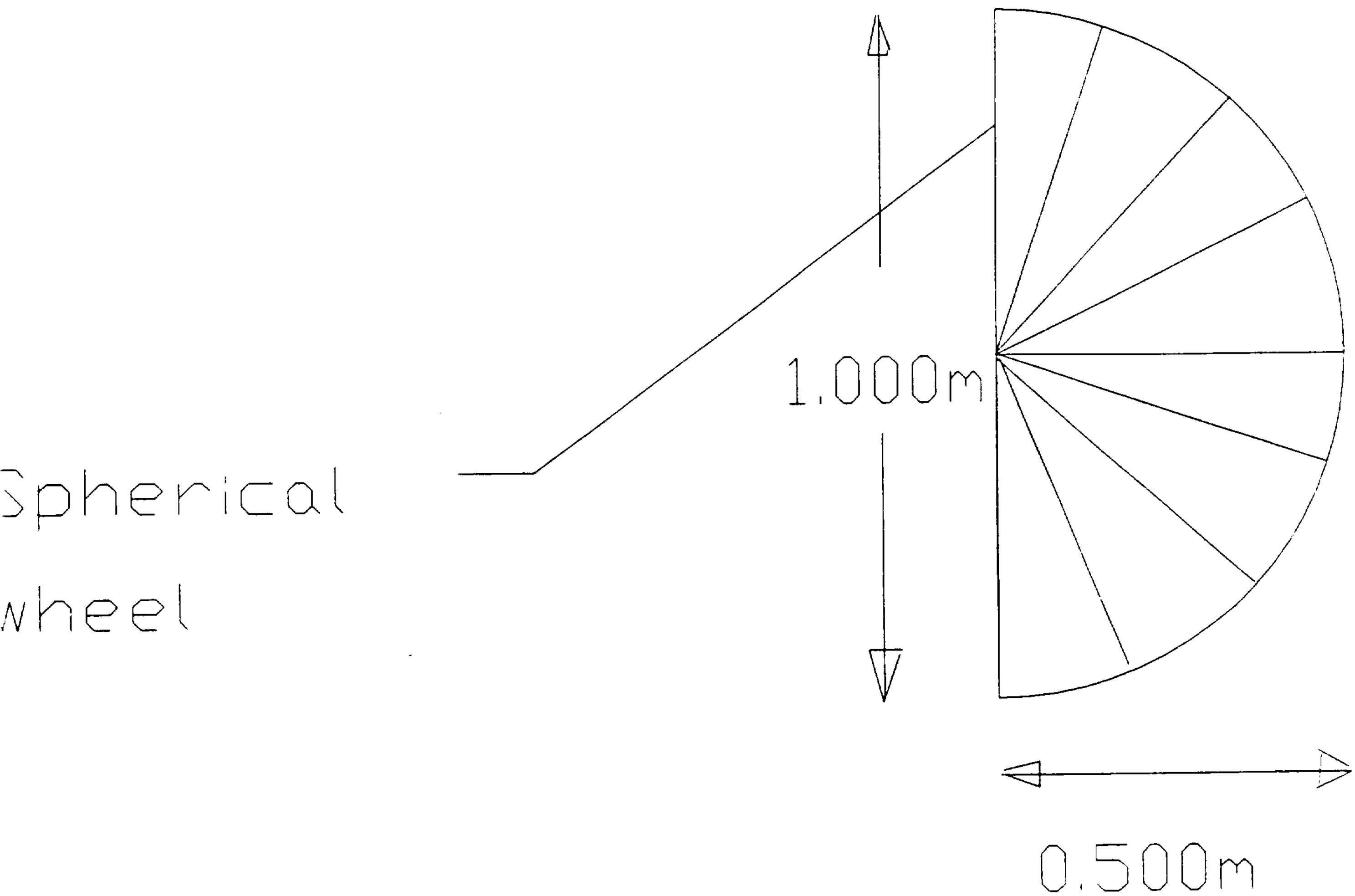


Figure 19

LUNAR VEHICLE WHEEL DESIGN



Side View

Figure 20

Lunar Rover Trailer

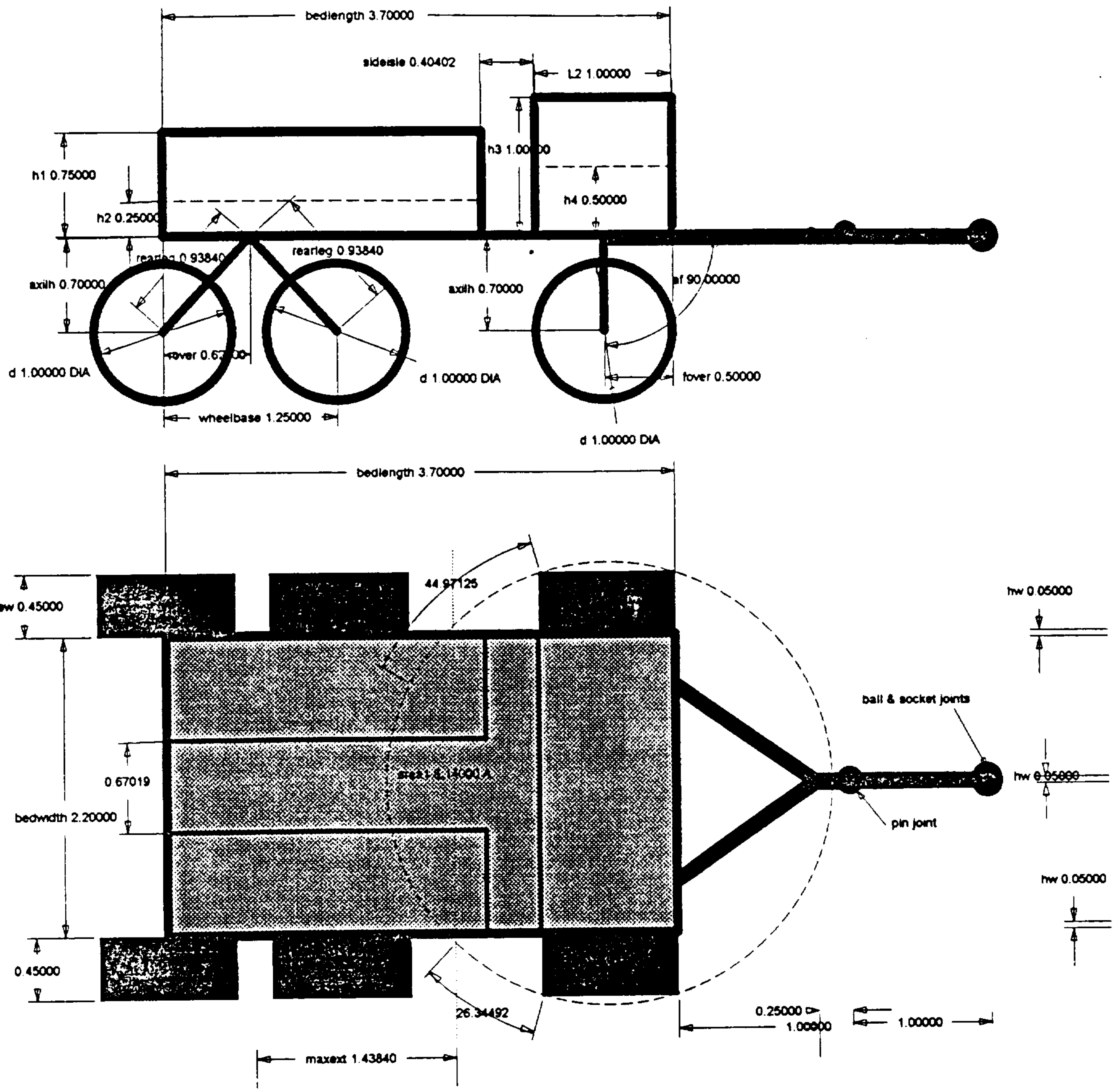


Figure 21

6.2 Appendix B: Pal Programs

This is a copy of the file used to construct the frame for PAL2 analysis.

```
Title EXAMPLE -- Chassis
nodal point locations
1 0, 0, 0
2 .625, 0, 0
3 3.1, 0, 0
4 3.6, 0, 0
5 3.6, 2.1, 0
6 3.1, 2.1, 0
7 .625, 2.1, 0
8 0, 2.1, 0
9 1.863, 1.05, 0
10 3.1, 0.888, 0
11 3.1, 1.213, 0
12 3.6, 1.213, 0
13 3.6, 0.888, 0
-- BLANK LINE --
material properties 40.6805e9, 581.2e6, 1677, .1, 1.17e9
beam type 1, 4.05e-3, 8.424e-6, 5.9e-6, 2.52e-6, 0, 0, 1.18e-4, 5.04e-5
connect 1 to 2
connect 1 to 8
connect 8 to 7
connect 7 to 6
connect 6 to 5
connect 5 to 12
connect 4 to 3
connect 3 to 2
connect 2 to 9
connect 3 to 9
connect 6 to 9
connect 7 to 9
connect 12 to 13
connect 13 to 4
connect 3 to 10
connect 10 to 11
connect 11 to 6
connect 11 to 12
connect 10 to 13
end definition
```

The following is a copy of the file used to specify the forces on the frame for analysis using PAL2.

```
DISPLACEMENTS APPLIED 1
TZ 0 2 3 6 7
TX 0 2 7
TY 0 2 3

FORCES AND MOMENTS APPLIED 1
FZ -8800 1 2 3 4 5 6 7 8 9 10 11 12 13
FX 60000 11 10

SOLVE
QUIT
```

The following is a copy of the file created, displaying the results of a PAL2 analysis on the frame.

```
04-16-93 16:04          MSC/pal 2          Page 1

     EXAMPLE 1 -- TWO POINT CANTILEVER BEAM ANALYSIS

   STATIC  ANALYSIS  SUBCASE NO.  1   APPLIED FORCES

 NODE DIR  VALUE      NODE DIR  VALUE      NODE DIR  VALUE
   1 Z T  -8.800E+03    2 Z T  -8.800E+03    3 Z T  -8.800E+03
   4 Z T  -8.800E+03    5 Z T  -8.800E+03    6 Z T  -8.800E+03
   7 Z T  -8.800E+03    8 Z T  -8.800E+03    9 Z T  -8.800E+03
  10 X T   6.000E+04   10 Z T  -8.800E+03   11 X T   6.000E+04
  11 Z T  -8.800E+03   12 Z T  -8.800E+03   13 Z T  -8.800E+03

   STATIC  ANALYSIS  SUBCASE NO.  1   EXTERNAL FORCES
```

NODE	DIR	VALUE	NODE	DIR	VALUE	NODE	DIR	VALUE
2	X T	-6.736E+04	2	Y T	-6.269E+03	2	Z T	1.847E+04
3	Y T	6.269E+03	3	Z T	3.873E+04	6	Z T	3.874E+04
7	X T	-5.264E+04	7	Z T	1.847E+04			

STATIC ANALYSIS SUBCASE NO. 1 DISPLACEMENTS

NODE	X TRANS	Y TRANS	Z TRANS	X ROT	Y ROT	Z ROT
1	1.4359E-08	-5.6625E-04	-2.0262E-02	-1.1757E-03	-3.4806E-02	7.0166E-04
2	0.0000E-01	0.0000E-01	0.0000E-01	-3.5441E-02	-2.7645E-02	1.0978E-03
3	9.0233E-04	0.0000E-01	0.0000E-01	-2.8208E-02	2.9699E-02	-8.3213E-03
4	9.8891E-04	-6.2037E-04	-1.7897E-02	-2.0380E-02	3.8811E-02	-1.2400E-02
5	8.7915E-04	2.1780E-05	-1.7903E-02	2.0380E-02	3.8825E-02	1.2546E-02
6	7.9251E-04	-6.7666E-04	0.0000E-01	2.8215E-02	2.9709E-02	8.4897E-03
7	0.0000E-01	-1.1006E-03	0.0000E-01	3.5445E-02	-2.7650E-02	-1.0221E-03
8	-1.4359E-08	-5.6650E-04	-2.0265E-02	1.1731E-03	-3.4811E-02	-6.7449E-04
9	5.2244E-04	-4.7649E-04	-2.2303E-03	6.9931E-07	-2.0475E-03	6.0618E-05
10	2.5975E-02	-2.5646E-04	-1.7535E-02	-6.5433E-03	2.7966E-02	-7.8263E-03
11	2.5950E-02	-4.2045E-04	-1.7529E-02	6.5754E-03	2.7970E-02	7.9811E-03
12	2.5863E-02	-2.1985E-04	-3.1521E-02	5.4400E-03	2.8022E-02	7.2667E-03
13	2.5889E-02	-3.7850E-04	-3.1525E-02	-5.4204E-03	2.8018E-02	-7.1103E-03

STATIC ANALYSIS SUBCASE NO. 1 ELEMENT RECOVERY

MAXIMUM STRESSES FOR BEAM VON MISES CRITERION

ELEMENT	MAJOR	MINOR	SHEAR	STRESS	% YIELD	@NODE	CONNECTIVITY	
1	-1.388E-14	-9.346E+02	4.673E+02	9.346E+02	0.0	1	1	2
2	-2.576E-14	-4.883E+03	2.442E+03	4.883E+03	0.0	1	1	8
3	9.346E+02	0.000E-01	4.673E+02	9.346E+02	0.0	8	8	7
4	1.303E+07	0.000E-01	6.513E+06	1.303E+07	1.1	7	7	6
5	7.050E+06	0.000E-01	3.525E+06	7.050E+06	0.6	5	6	5
6	1.108E+07	0.000E-01	5.541E+06	1.108E+07	0.9	12	5	12
7	7.043E+06	0.000E-01	3.522E+06	7.043E+06	0.6	3	4	3
8	1.483E+07	0.000E-01	7.416E+06	1.483E+07	1.3	2	3	2
9	2.261E+06	0.000E-01	1.131E+06	2.261E+06	0.2	9	2	9
10	-1.023E-12	-4.696E+05	2.348E+05	4.696E+05	0.0	3	3	9
11	1.915E+06	0.000E-01	9.573E+05	1.915E+06	0.2	9	6	9
12	-4.405E-13	-1.321E+05	6.604E+04	1.321E+05	0.0	7	7	9
13	1.986E+07	0.000E-01	9.929E+06	1.986E+07	1.7	12	12	13

14	1.108E+07	0.000E-01	5.540E+06	1.108E+07	0.9	13	13	4
15	2.910E-11	-1.175E+07	5.874E+06	1.175E+07	1.0	10	3	10
16	2.656E-10	-2.053E+07	1.026E+07	2.053E+07	1.8	11	10	11
17	-1.864E-11	-1.175E+07	5.875E+06	1.175E+07	1.0	11	11	6
18	3.206E-11	-7.048E+06	3.524E+06	7.048E+06	0.6	12	11	12
19	-2.979E-11	-7.045E+06	3.523E+06	7.045E+06	0.6	10	10	13

The following is a copy of the file used to create the hitch for PAL2 analysis.

```
TITLE EXAMPLE 1 -- HITCH ANALYSIS
NODAL POINT LOCATIONS 1
1, 0, 0, 0
2, .5, .35, 0
3, 1.0, .75, 0
4, 1.5, 1.1, 0
5, 1.0, 1.45, 0
6, 0.5, 1.85, 0
7, 0.0 2.2, 0
8, 1.75, 1.1, 0
9, 2.25, 1.1, 0
10, 2.75, 1.1, 0
11, 0, .4, 0
12, 0, .8, 0
13, 0, 1.4, 0
14, 0, 1.8, 0
-- BLANK LINE --
MATERIAL PROPERTIES 40.6805e9, 581.2e6, 1677, .1, 1.17e9
beam type 1, .03, 9.0625e-4, 6.25e-6, 0.0009
connect 1 to 11
connect 11 to 12
connect 13 to 14
connect 14 to 7
connect 12 to 4
connect 13 to 4
connect 12 ro 13
connect 4 to 8
beam type 1, .01025, 0.33644e-4, 0.2759e-6, 0.00003085
CONNECT 1 TO 2
connect 2 to 3
connect 3 to 4
connect 4 to 5
connect 5 to 6
```

connect 6 to 7
connect 8 to 9
connect 9 to 10
connect 13 to 6
connect 13 to 5
connect 12 to 3
connect 12 to 2
zero 1
RX 8
RY 8
RZ 8
END DEFINITION

The following is a copy of the file used to specify the forces applied for a PAL2 analysis.

DISPLACEMENTS APPLIED 1
TZ 0 1 7
TX 0 1 7
TY 0 1 7

FORCES AND MOMENTS APPLIED 1
FX 60000 8
FZ 24000 8
FZ -17500 13 12

SOLVE
QUIT

The following is a copy of the output from a PAL2 Analysis on the hitch.

```
04-18-93 20:29          MSC/pal 2               Page  1

     EXAMPLE 1 -- HITCH ANALYSIS

   STATIC  ANALYSIS  SUBCASE NO.  1   APPLIED FORCES

 NODE  DIR   VALUE     NODE  DIR   VALUE     NODE  DIR   VALUE
  8  X T  6.000E+04    8  Z T  2.400E+04   12  Z T  -1.750E+04
 13  Z T  -1.750E+04
```

STATIC ANALYSIS SUBCASE NO. 1 EXTERNAL FORCES

NODE	DIR	VALUE	NODE	DIR	VALUE	NODE	DIR	VALUE
1	X T	-3.000E+04	1	Y T	-1.433E+04	1	Z T	5.500E+03
7	X T	-3.000E+04	7	Y T	1.433E+04	7	Z T	5.500E+03

STATIC ANALYSIS SUBCASE NO. 1 DISPLACEMENTS

NODE	X TRANS	Y TRANS	Z TRANS	X ROT	Y ROT	Z ROT
1	0.0000E-01	0.0000E-01	0.0000E-01	-6.8910E-03	-8.6577E-02	-1.5527E-04
2	6.1853E-05	-3.4361E-05	3.9495E-02	-3.1206E-03	-8.0647E-02	-6.9786E-05
3	9.7508E-05	-2.8665E-05	7.6353E-02	8.8687E-04	-6.8970E-02	5.4702E-06
4	1.1512E-04	-5.8584E-20	1.0377E-01	-1.6450E-18	-3.8348E-02	-2.3062E-20
5	9.7508E-05	2.8665E-05	7.6353E-02	-8.8687E-04	-6.8970E-02	-5.4702E-06
6	6.1853E-05	3.4361E-05	3.9495E-02	3.1206E-03	-8.0647E-02	6.9786E-05
7	0.0000E-01	0.0000E-01	0.0000E-01	6.8910E-03	-8.6577E-02	1.5527E-04
8	1.2741E-04	-6.1466E-20	1.0868E-01	0.0000E-01	0.0000E-01	0.0000E-01
9	1.2741E-04	-6.1466E-20	1.0868E-01	0.0000E-01	0.0000E-01	0.0000E-01
10	1.2741E-04	-6.1466E-20	1.0868E-01	0.0000E-01	0.0000E-01	0.0000E-01
11	5.8970E-05	6.2878E-07	-2.5660E-03	-5.3967E-03	-8.6762E-02	-1.3021E-04
12	9.6675E-05	1.2576E-06	-3.8837E-03	-6.4968E-04	-8.6946E-02	-4.8949E-05
13	9.6675E-05	-1.2576E-06	-3.8837E-03	6.4968E-04	-8.6946E-02	4.8949E-05
14	5.8970E-05	-6.2878E-07	-2.5660E-03	5.3967E-03	-8.6762E-02	1.3021E-04

STATIC ANALYSIS SUBCASE NO. 1 ELEMENT RECOVERY

MAXIMUM STRESSES FOR BEAM VON MISES CRITERION

ELEMENT	MAJOR	MINOR	SHEAR	STRESS	% YIELD	@NODE	CONNECTIVITY	
1	6.395E+04	0.000E-01	3.197E+04	6.395E+04	0.0	1	1	11
2	6.395E+04	0.000E-01	3.197E+04	6.395E+04	0.0	12	11	12
3	6.395E+04	0.000E-01	3.197E+04	6.395E+04	0.0	14	13	14
4	6.395E+04	0.000E-01	3.197E+04	6.395E+04	0.0	7	14	7
5	4.744E+05	0.000E-01	2.372E+05	4.744E+05	0.0	12	12	4
6	4.744E+05	0.000E-01	2.372E+05	4.744E+05	0.0	13	13	4
7	-2.700E-12	-1.705E+05	8.526E+04	1.705E+05	0.0	12	12	13
8	2.000E+06	0.000E-01	1.000E+06	2.000E+06	0.2	8	4	8
9	2.064E+06	0.000E-01	1.032E+06	2.064E+06	0.2	1	1	2
10	1.995E+06	0.000E-01	9.975E+05	1.995E+06	0.2	3	2	3

11	2.057E+06	0.000E-01	1.029E+06	2.057E+06	0.2	3	3	4
12	2.057E+06	0.000E-01	1.029E+06	2.057E+06	0.2	5	4	5
13	1.995E+06	0.000E-01	9.975E+05	1.995E+06	0.2	6	5	6
14	2.064E+06	0.000E-01	1.032E+06	2.064E+06	0.2	6	6	7
17	-1.783E-12	-1.243E+05	6.213E+04	1.243E+05	0.0	13	13	6
18	9.453E+04	0.000E-01	4.727E+04	9.453E+04	0.0	5	13	5
19	9.453E+04	0.000E-01	4.727E+04	9.453E+04	0.0	3	12	3
20	1.730E-12	-1.243E+05	6.213E+04	1.243E+05	0.0	2	12	2

6.3 Appendix C: Calculations

MATERIAL: Carbon graphite composite material

$E = 40.6805 * 10^9$ Pa
$\sigma = 1677.3$ kg/m^3
$v = 0.3$
$s_y = 1.17 * 10^9$ Pa
$\tau =$
$G =$

Factor of safety for all calculations: 3.0

BED THICKNESS

Calculations based on earth's gravity (Moon's gravity = 1/6 earth gravity)

Maximum load : (7,000 kg) (9.81m/s^2) = 68,670 N/2 = 34,355N

Area(cross-section) = bh = (2.2m)h

Longitudinal stress:

$\sigma_x = Mh/2 / 1/12bh^3$

$h^3/h = Mh(12)/2b\sigma_x$; $h^2 = 12 M/ 2b\sigma_x$

$h = (12M/2b\sigma_x)^{1/2}$; h = .012168m = using t = .015m

Acceptable deflection: 0.02m

Maximum deflection: $Y_{max} = -PL_3/48EI$ $I = 1/12bh^3$

Solving for h: $h^3 = -PL^3/Y_{max}$ (48)E(b)(.0833333) = 2.4297062E-4m

h = thickness(t): 0.624m = t = 0.060m

BODY CALCULATIONS

Body wall thickness:

Hydrostatic assumption σ_{max} (sand) = $1600 kg/m^3$

Pressure max = σgh = 1600(9.81)(0.75) = 11772 Pa

$Area_{(wall)} = 0.75(1.15) = 0.8625\ m^3$

$Pressure_{(avg)} = 1/2\ P_{max} = 11772/2 = 5886$ Pa

Force on wall = $F_{wall} = PA = 5886(0.8625) = 5076.675N$

Maximum shearing stress $\tau_{max} = 3\ F_{max}\ /2\ A_c = 3\ F_{max}/2Lt$

$t = 1.7356*10^{-5}$ m

BENDING

Longitudinal stress: $\sigma_x = My/I$

M = 2/3L(1/2)F = 2/3(0.75)(t/2)(5076.675) = 1269.17 t

$\sigma_x = M\ t/2\ /\ I;\ \ I = 1/12bt^3 = 1.15t^3\ /12 = 0.09583t^3$

$\sigma_x = 1269.17(0.5)/0.09583t^2 = 6621.76/t^2;\ \ 6621.76/\sigma_x$

$t^2 = 5.66 * 10^{-6}$: $t = 0.00238m$

DEFLECTION

$X_{max} = -Fb(L^2 - b^2)^{1.5}/9(3)^{1/2}$ EIL: a = 0.50, b = 0.25, L = 0.75

$X_{max} = 2538.34(.25)(.5)^{1.5}/9(3)^{1/2}$ (40.6805E9)(0.09583 t^3)(0.75)= $5x10^{-9}/t^3$

Acceptable deflection: $X_{max} = 0.005m$; t = 0.01m = 1.0cm

TRAILER WEIGHT CALCULATIONS

BODY

COMPONENT	VOLUME
Compartment 1	0.0456 m^3
Compartment 2	0.0456 m^3
Top (V_3)	0.01759 m^3
Top (V_4)	0.01759 m^3
Seat (V_5)	0.02158m^3
Seat walls(V_6)	0.04180m^3
Center walls (V_7)	0.0055875m^3
TOTAL	0.1954m^3
MASS =	64.013 kg

TRAILER WEIGHT CALCULATIONS

FLOOR PLATING

$M = \sigma V$: $V = (b\ h\ t)\ \sigma$

$= (3.7)(2.2)(.06)(1677.3)$

$= 819.2$ kg

FRAME

Component	Mass (kg)
I-beam (1):	14.265
I-beam (2):	14.265
I-beam (3):	14.265
I-beam (4):	24.455
I-beam (5):	24.455
I-beam (6):	22.100
I-beam (7):	22.100
I-beam (8):	3.400
I-beam (9):	3.400
TOTAL:	142.705 kg

TWO DEGREE OF FREEDOM SYSTEM FOR SUSPENSION SYSTEM

DIFFERENTIAL EQUATIONS OF MOTION

$my'' = -k_1 (y - L/2\, \theta) - k_2 (y + L/2\, \theta)$

$I\theta'' = k_1 (y - L/2\, \theta)\, L/2 \cos\theta - k_2 (y + L/2\, \theta)$

assume small angular oscillations therefore $\cos\theta = 1$

thus

$my'' + (k_1 + k_2)\, y + (k_2 - k_1)\, L/2\, \theta = 0$

$I\, \theta'' + (k_2 + k_1)\, L^2/4\, \theta + (k_2 - k_1)\, L/2\, y = 0$

In matrix form

$$\begin{array}{cccc} M & x'' & K & x \\ \begin{matrix} m & 0 \\ 0 & I \end{matrix} & \begin{matrix} y'' \\ \theta'' \end{matrix} & \begin{matrix} k_1 + k_2 & (k_2 - k_1)\, L/2 \\ (k_2 - k_1)\, L/2 & (k_2 + k_1)\, L^2/4 \end{matrix} & \begin{matrix} y \\ \theta \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} \end{array}$$

assume the solution $x = X \sin(\omega t + \phi)$ where X is the vector of amplitudes

$x'' = -\omega^2 X \sin(\omega t + \phi)$

$$X = \begin{matrix} Y \\ \theta \end{matrix}$$

after substitution $\quad K - \omega^2 M \quad X = 0$

for solution the determinant = 0

$K - \omega^2 M = 0$ thus

$$\begin{matrix} k_{11} - \omega^2 m & k_{12} \\ k_{21} & k_{22} - \omega^2 I \end{matrix}$$

thus

$\omega^4 I m - \omega^2 (k_1 + k_2)(m L^2/4 + I) + 4 k_1 k_2 L^2/4 = 0$

solve for roots

$a = mI$

$b = -(k_1 + k_2)(mL^2/4 + I)$

$c = 4k_1k_2 L^2/4$

the amplitude ratios β_1 and β_2

$\beta_1 = X_{11}/ X_{21}$

$\beta_2 = X_{12} / X_{22}$

thus the solution is given by

$y = x_1 = \beta_1 X_{21} \sin(\omega_1 t + \phi_1) + \beta_2 X_{22} \sin(\omega_2 t + \phi_2)$

$\theta = x_2 = X_{21} \sin(\omega_1 t + \phi_1) + X_{22} \sin(\omega_2 t + \phi_2)$

Vehicle Hitch Attachment

Titanium

$\tau_y = 825$ MPa

$\sigma_y = 825$ MPa

$P = 60{,}000$ N

F.S. = 6.0

$\tau_{all} = 825/3 = 275$ MPa

$\tau_{all} = P/A = P/2/\ \pi d^2/4$

$d^2 = P^2/4\pi\tau_{all}$

d = 0.011785536m using 1.5 cm

Hitch Arm Dimensions

$\tau = P/A = P/w(t+d)$

$t = (P/\ \tau\ w\ ) + d$

t = 60,000/275E6(0.02) + 0.011785536m

t = 0.022694627 m using 2.5 cm

Assuming worst case (trailer hitch attachment is in bending)

$\sigma = My/I$

$I = 1/12\ bh^3$

Solving for b: $b = 12\ My/\sigma h^3 = 12(0.02)(30{,}000)(0.09)\ /\ (275e6)(0.045)^3$

b = 2.586 cm

Design check:

Area = (b - d)(w) = (0.026 - 0.015) (0.09) = .0009774

$\sigma = F\ /\ A\ =\ 30{,}000\ /\ 0.0009774\ =\ 30.7$ MPa

30.7 MPa < 275 MPa: Therefore, width is acceptable.

7.0 References

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